Presented at the Annual Meeting, 7th Wissen Gesell Luft- und Raumfahrt, Munich Germany
~~WGLR~~ Munich, Germany, October 1963 Oct. 1963

~~X64 10735~~ N65-88993

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[1963] 60p refs

[7] conf

10735

code 2A

GROUND STATIONS FOR DEEP SPACE EXPLORATION**

(NASA CR 5...)

Summary

At the present time radio is the only practical means of communicating with spacecraft. In order to meet the great range of communication requirements for spacecraft in deep space, precision versatile radio ground stations are needed whose design is the result of the careful integration of many factors. Among these factors are; high gain antennas, low noise feeds and preamplifiers, high power transmitters, microwave frequencies, accurate timing systems, variable data rates, logistics and the operation of stations in remote locations. The stations are required to receive and record data, send command and control signals to the spacecraft, and to provide tracking information so that the location of the spacecraft in space will be accurately known.

The interrelationship of the design factors with the spacecraft communication requirements are presented. Station and system site requirements and equipment and system capabilities are developed and illustrated by an example of present design.

Author

1. INTRODUCTION

1.1 Typical Deep Space Exploration Project Requirements

By deep space is meant distances as far as the Moon and beyond. Deep space exploration implies the scientific determination of the space environment and the use of these findings in extending our knowledge of nature. For this purpose, the United States Program for deep space exploration includes plans for sending scientifically instrumented spacecraft to the vicinity and the surface of the Moon and the near planets. For

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**This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract ~~No.~~ NAS 7-100 sponsored by the National Aeronautics and Space Administration.

(NASA

example, one of the missions of the Ranger project is to obtain television pictures of the lunar surface which will be of benefit to both the scientific investigation of the Moon and the manned flights to the Moon. The Surveyor program will soft-land a spacecraft on the Moon in such a way that it will be able to obtain television pictures of the surface of the Moon and to sample the surface material. The Mariner program is designed to send spacecraft in the vicinity of the near planets to obtain pictures of the planets and to make cis-planetary and near-planetary measurements of fields and particles. The Voyager program will send spacecraft to the vicinity of the planets and will land instruments which will measure the characteristics of the surface material. Later it may be possible to return samples of the surface to the Earth for further examination.

In order to accomplish these exploration objectives it is necessary to communicate with the spacecraft. Table 1 illustrates typical deep space communication requirements. Details of these requirements will vary depending upon the mission of the spacecraft: whether it will make a hard or soft landing, orbit the planet or the Moon,land and return material, and whether spacecraft storage facilities will be available for the returning of data at a slow rate. It will be noted that Table 1 separates the communications requirements into three categories: tracking, data acquisition, and command and control.* Tracking means determining the position of the spacecraft from measurements of range, direction, and velocity (Bild (Fig.) 1). Data acquisition means the reception of telemetered measurements made by sensors in the spacecraft (Bild (Fig.) 2), and command and control is the transmission of information to the spacecraft asking it to perform a specific function (Bild (Fig.) 3).

*This concept was presented by G. M. Truszynski of NASA in a talk, "Space Communications" at the Seventh Annual Meeting of the Air Traffic Control Association, Las Vegas, Nevada, Oct. 2, 1962.

Table 1. Typical deep space communication requirements

Tracking	Lunar	Planetary
Injection		
Position, meters	100	100
Angle, deg	0.5	0.5
Velocity, meters per sec	1	1
Midcourse		
Position, meters	10	10
Angle, deg	0.05	0.05
Velocity, meters per sec	0.01	0.01
Terminal		
Position, meters	10	1000
Angle, deg	0.05	none
Velocity, meters per sec	0.002	0.002
Data Acquisition	Lunar	Planetary
Modulation bandwidth, kc	1000	6
Signal to noise ratio, db	35	6
Time Duration (percent of mission life)	100	50
Command and Control	Lunar	Planetary
Modulation bandwidth, kc	1	0.1
Error rate	10^{-6}	10^{-6}
Time duration each command, sec	5	15
Command verification	yes	yes
Command execution verification	yes	yes

1.2 Basic Ground Station Requirements

At the present time radio provides the only practical means of communicating with deep-space spacecraft. In order to maintain continuous communications it is necessary to provide radio stations that are located approximately 120 deg apart on the Earth's surface. Then as the Earth rotates, one of the stations will always be able to receive and send radio signals to the spacecraft (Bild (Fig.) 4). The basic ground station requirements therefore, are:

1. An antenna capable of being pointed at the spacecraft and sensitive enough to receive very weak signals (Ref. 1).
2. Antenna feeds designed to match the polarization of the signals from the spacecraft and which will furnish angular error signals to the antenna servo drive mechanism.
3. Very low noise preamplifiers
4. A sensitive receiving system which will match the communications equipment in the spacecraft and which will detect, demodulate and decommutate the signals.
5. A recording system which will satisfactorily record the detected signals from the receiver.
6. A data system which will provide precise timing signals and will record the required station data which will later be used in data reduction of the telemetry information.
7. A high-powered transmitter and frequency synthesizer.
8. A diplexer and filters which will allow the transmitter and receiver to transmit and receive simultaneously on separate frequencies, with no significant degradation.
9. Buildings, roads, etc. for the logistics support of the people operating the station.

10. A station site capable of being operated by technical personnel and which is unaffected by extraneous noises either natural or man-made.

2. SITE REQUIREMENTS

The siting of a deep space radio station is one of the most important factors in establishing a network of such stations for communications with spacecraft in deep space. Of the almost infinite number of siting requirements which could be listed only the most important will be considered in this paper. No attempt will be made to list them in the order of priority.

2.1. Logistics, Area and Noise Requirements

Of prime importance in the location of any deep space tracking station is the requirement that it be capable of being supported by the people who will operate it. This generally requires that the stations be located within one hour's driving time of a major city where the operational personnel and their families can obtain satisfactory living accommodations. This includes recreation, police and fire protection, shopping centers, schools, etc. Although it is possible to furnish most of these requirements as part of the logistics support to a remote location, experience has shown that it is difficult to recruit qualified technical personnel to live at areas areas remote from large urban facilities.

Local roads must be hard-surfaced, all-weather roads capable of carrying large freight trucks with loads up to 20 tons. The roads should have no obstructions such as tunnels or bridges which will prevent the transportation of large items of equipment. It is highly desirable that daily air service be available to international air connections. Communications must be available to an international communications service which is capable of furnishing a minimum of two voice channels and three full-period teleprinter circuits.

A satisfactory site should be large enough to accommodate the buildings and the antenna including a location for a collimation tower which may be as far as 1 or 2 miles from the antenna. This site should be available for purchase or long-term lease and should be located in a bowl in the hills or mountains which will shield it from all sources of man-made interference (Ref. 2). The bowl should not have a horizon mask greater than 5-6 deg in any direction. It is also desirable, in most instances, that areas for several contiguous sites for other antennas be available. The area should not be subject to extremes of weather, such as hurricanes, tornadoes or high prevailing winds, or excessive temperatures; nor should it be subject to tidal waves or earthquakes over 3° Richter. The soil should have good drainage and be capable of supporting heavy mechanical structures and buildings. It is also ~~important~~ highly desirable that the site be free of any scheduled or proposed aircraft routes. These major site requirements are summarized in Tables 2 and 3.

2.2 Location

~~Because the antennas generally will have polar mounts, it is desirable to locate them within ±40° latitude. The longitude locations of the stations are heavily dependent upon the location of the Launch Facility. In the United States this, of course, is Cape Canaveral, Florida, and spacecraft launched from this location generally follow a trajectory which carries them over the South Atlantic and South Africa. This requires that our first two deep space stations be located in the Southern Hemisphere.~~

Bild (Fig.) 5 shows on a map of the World the three sites for the deep space stations selected to support the United States deep space exploration projects. These locations are near Goldstone, California; Johannesburg, South Africa; and Woomera, Australia. On the map are irregular circles which indicate the ground distance over which the station can communicate with the spacecraft when it is at a given altitude. It will be noted that when the spacecraft reaches an altitude of about 10,000 miles the station

Table 2. Major site requirements for a Deep Space Communication Station

1. Logistic requirements (Table 3)
2. A location within ±40 deg latitude and 120 ±10 deg longitude from other deep space stations
3. An area of approximately 10 acres obtainable by purchase or long-term lease
4. An area of at least 250 sq yd for a collimation tower, located 1-2 mi from the antenna and available by a surfaced road.
5. A location shielded by hills or mountains from all sources of man-made radio interference, such as radar, radio and television stations, cities, main roads, high voltage transmission lines, etc.
6. A horizon mask not greater than 5 deg in all directions
7. A surface that is essentially level with good drainage
8. A location that is not subject to tidal waves or earthquakes above 3 deg Richter
9. A subsoil that is stable and solid enough to support heavy structures
10. A soil that is capable of sewage disposal through use of septic tanks and cesspools
11. Weather that is mild with no extremes and no high prevailing or gusty winds, a minimum number of thunder and hailstorms, cyclones, tornadoes and hurricanes, a low rain and snow fall, and a mild temperature and humidity range
12. An adequate source of potable water at a reasonable cost
13. A location outside the path of scheduled aircraft routes
14. Agreements for means of controlling RF interference caused by governmental and civilian radio, radar, etc.

Table 3. Major logistic requirements for a Deep Space Communication Station

One hour's driving time or less to a city which can furnish the following facilities to about 60 families and 40 transient workers:

1. Housing, obtainable by renting or by purchase
2. Stores of all kinds
3. Police and fire protection
4. Schools
5. Entertainment
6. Medical, dental, and legal facilities
7. Local transportation and communication facilities
8. Hotels
9. Roads, all-weather graded, capable of carrying trucks with 20-ton loads
10. Daily air service to international air terminals
11. Rail or heavy truck service to a major seaport
12. Rental aircraft
13. Rental automobiles and trucks
14. Telephone and teleprinter circuits to an international communication carrier
15. Skilled and unskilled labor

Three hour's driving time or less to a city which can furnish the following additional support:

1. Heavy construction facilities
2. Fuel, diesel and gasoline
3. Engineering service: architectural, geological, etc.
4. Parts fabrication and repair shops: mechanical, electronic, diesel, etc.

— in the latitude band ± 30° (where our targets are)

coverage circles overlap each other, thus allowing 24-hour-a-day coverage for a given spacecraft. Bild (Fig.) 6 shows the relationship between the ground distance from the station to the sub-vehicle point at beginning of visibility and the elevation angle above the horizon in degrees for different spacecraft altitudes. The tracking and data acquisition of spacecraft from the time of launch until it is acquired by one of these permanent deep space stations is accomplished either by fixed or portable stations located down-range from Cape Canaveral and operated by the Atlantic Missile Range.

2.3 Operations

In tracking and obtaining data from a deep space probe on a 24-hour-a-day-basis, each station of a three station network is required to track and obtain data for a minimum of eight hours. In addition to this, the station must be prepared for operations by testing each equipment component and by calibrating all of the instruments which measure voltages, currents, frequencies, power, etc., which will be used in later data reduction. Our experience shows that this time is quite variable but on the average requires three hours for preparation and calibration and one hour for shut-down time. This is a total of at least 12 hours per day and on a seven-day-a-week basis requires at least two shifts of operators. If the network is responsible for more than one spacecraft or if installation or modification work is to be done, additional shifts of operators will be required. Also, since the tracking time may occur at any time during the day or night, it is necessary to maintain very flexible working hours. Some amenities at the station to support the operating people are very desirable. These may include such things as food service and dormitory facilities and should be included in any plans for station operation.

3. STATION CAPABILITIES

A deep space station is essentially a precision radio tracking system which measures two angles; radial velocity and range, and communicates with a spacecraft in an efficient and reliable manner. Because deep space spacecraft are characterized by low angular rates, generally low data rates, and very weak signals, the deep space station must be designed with these characteristics in mind. Bild (Fig.) 7 is a block diagram of a typical deep space station.

3.1 Antenna

The ground antenna is probably the most important single component of a deep space communication system. We depend upon it to gather enough energy from the extremely low power density available from the spacecraft to override the noise input to the receiver preamplifier. This is illustrated in Bild (Fig.) 8 which shows that the signal power at the input of the ground receiver is equal to:

$$P_R = \frac{P_T A_T G_R}{4\pi R^2}$$

Since the space vehicle antenna area and transmitter power are closely related to its physical size and weight the received signal power is mainly dependent upon the ground antenna gain.

Various types of antennas have been tried but the type most universally used is the paraboloidal reflector. It is non-frequency selective and, within limits, provides the highest gain for the lowest cost (Ref. 3 and 4). Because the cost of large parabolic antennas varies ~~approximately~~ at least as the 2.7 power of the diameter there is an economic limit to the size of the antenna, and because of technical construction difficulties there is a practical limit to its size. Present day state-of-the-art indicates maximum gains of about 62 db using antenna diameters between 85 and 250 ft and operating frequencies below 10 Gc.

The effective gain of a parabolic antenna is equal to:

$$G = \left(\frac{\pi D}{\lambda}\right)^2 \eta = \frac{4\pi A_R}{\lambda^2}$$

where

D = Diameter

λ = Wavelength

η = Antenna efficiency (presently about 0.5 to 0.6)

A_R = Effective Antenna Area

A better measure of the effectiveness of an antenna than the gain is the expression A_R/T_S or $\lambda^2 G/4\pi\eta T_S$ which is commonly referred to as the figure of merit. ~~A = antenna area, and~~ (where T_S = system noise temperature at the receiver input)[*] This relates the effective area of an antenna to the system noise and therefore includes the feed design and the circuitry losses.

Factors which must be considered in the design of antennas are:

1. Cost
2. Capability of being pointed at any specified direction in the hemisphere and of being driven smoothly on both axes at both sidereal and slew rates. If polar mounts are used, the hemispherical coverage may be reduced by the usual polar axis limitations.
3. The distortion of the parabolic reflector surface and pointing reference due to temperature changes or differences (Ref. 1), wind, rain, snow, hail, gravity, and steering acceleration.
4. Effect of wind on the drive system due to unbalanced forces at different antenna attitudes.
5. Resonance
6. Antenna safety under extreme environmental conditions.
7. Capability of measuring and adjusting the reflector surface, the positions of the axes

[*] D. Schuster, "Antenna Temperatures," a lecture given to Jet Propulsion Laboratory Research Conference, November, 1960

(orthogonality, etc.), the gears and limit switches and stops, position indicators and feed location.

8. Freedom from back lash and "wobble."
9. Easy and safe accessibility to operating areas.
10. Method of aligning and measuring the alignment of the mechanical and RF axes and of maintaining the accuracy of alignment.
11. Operating life.
12. Cost of maintenance and operation.
13. Reliability.

At the present time, 85-ft diameter polar-mount antennas are used in the Deep Space Instrumentation Facility to communicate with deep space probes. A 210-ft diameter antenna is being designed and will be constructed at the Goldstone Tracking Station in California. ~~Additional 210-ft antennas will be built~~ [redacted] The characteristics of the 85-ft antennas and the anticipated characteristics of the 210-ft antennas are shown in Table 4.

Bild (Fig.) 9 shows a typical 85-ft antenna with cassegrain cone in use in the DSIF.

5.2 Transmitter

The ground transmitter is used in the earth-to-spacecraft communications link and is used for the sending of commands and ranging data, and to obtain two-way coherent doppler information. Because very low noise preamplifiers are not yet available for use on spacecraft, their receivers usually have an input noise temperature of about 2000° K and are consequently about 16 db less sensitive than the ground receiver with a maser input. The receiving antenna on the spacecraft is usually an omnidirectional unit since it may be necessary to send commands even when the directional antenna is not pointed towards the Earth. The difference in gain between the two antennas is usually from 18-20 db. The resultant 34-36 db ~~loss~~ difference in

Table 4. Characteristics of 85- and 210-ft antennas

Diameter	85 ft	210 ft
Mount	Polar	Az-El
Feed configuration	Cassegrain	Cassegrain
Ellipticity, db	0.7	0.7
Gain 960 Mc/s with tracking feed, db	43.0	---
2295 Mc/s with tracking feed, db	53.0	61.0
Polarization	Right circular	Right circular
Beamwidth, deg (2295 Mc)	0.35	0.15
Maximum angular rate, deg/sec	1.0	0.25
Minimum angular rate, deg/sec	0	0
Pointing accuracy, deg	0.1	0.04
Angle measurement resolution, degrees	0.002	0.002
Effective antenna noise temperature, °K	30	35

sensitivity for the Earth-to-spacecraft link requires CW transmitter powers on the order of 10 kw and for certain [redacted] modes, power up to 100 kw is required.

The transmitter consists of a power amplifier using a single klystron, a modulator and exciter, a heat exchanger and a power supply unit. The power amplifier is mounted in a cage on the back of the antenna reflector with the output power carried to the cassegrain feed system by means of coaxial line or waveguide. Power control, monitoring and safety interlock and protective equipment are also mounted in the cage. The high-voltage power supply unit and heat exchanger which furnishes liquid coolant to the klystron are mounted on the ground near the antenna. The power supply unit is inside a building, while the heat exchanger is generally outside. The exciter and modulator for the power amplifier are located in the antenna control room.

The characteristics of a typical 10-kw transmitter are listed in Table 5. Bild (Fig.) 10 shows a typical 10-kw power amplifier installation in an antenna and Bild (Fig.) 12 ~~11~~ shows a heat exchanger. A power supply unit with the door to the rectifier compartment open is shown in Bild (Fig.) ~~12.~~ 11

3.3 Receiver and Preamplifiers

Noise is the limiting factor in communications, and it originates from many sources both man-made and natural. This is the primary reason for selecting the sites of deep space data acquisition stations in locations which are surrounded by hills or low mountains and are located far from man-made electromagnetic radiation. Hills and mountains help provide shielding from these sources. Man-made noise generally results from radio, radar and television transmitters, automotive ignition, high-voltage transmission lines (corona and arcing), diathermy, and similar equipment and electrical switching. Natural noise sources include galactic sources such as the sky background, radio stars, Moon and the Sun, atmospheric absorption

Table 5. Characteristics of typical 10-kw transmitter

<u>Power amplifier</u>	
Klystron type	Varian 833C
Operating frequency	890 6[redacted]5 Mc
Max output power	10 kw
Gain	40 db
Bandwidth (broadband tuned)	12 Mc
Beam voltage	12.5 kv
Beam current	2.7 amperes
Focusing magnet	Electromagnet
<u>Heat exchanger</u>	
Heat exchanger capacity (135°F ambient)	50 kw
Coolant rate	27 gal/min
Static head	100 ft
Coolant heater	15 kw
<u>Power supply</u>	
Input power	460 vac 400 cycle 3 phase 50 kva
Output capacity	13000 vdc at 3amp, or 20000 vdc at 2-1/2 amp
Ripple	0.1 percent
Rectifier	3-phase vacuum tube

(primarily oxygen and water vapor), ionospheric attenuation, storms and lightning, resistive losses in electric circuitry such as waveguides, coaxial lines, switches, reflector surface, etc., and in thermal noise of the receiver components. Bild (Fig.) 13 is an artist's sketch of some typical noise sources, and Bild (Fig.) 14 shows a diagram of an equivalent noise circuit in the input of a preamplifier. Bild (Fig.) 15 shows the variation of galactic and atmospheric noise temperature sources with frequency and gives a measure of their relative intensity.

For deep space communications it is desirable to minimize the noise from galactic and atmospheric sources. For this reason, where possible, spacecraft trajectories are selected to avoid the Sun, Moon and the more intense radio stars, and when the received signal strength approaches threshold, the ground stations are scheduled to acquire data only at the higher elevation angles. Also the communication frequencies are generally selected to be between 1 and 10 gigacycles.

In order to reduce the thermal noise in the receiver input circuits, low-noise preamplifiers of the parametric and maser types are used. The parametric amplifier reduces the thermal noise input from about 1500° K, which is the system noise temperature with a well designed low-noise receiver input circuit, to about 200° K, which is the system noise temperature with the usual uncooled parametric amplifier unit. This is an 8-1/2 db reduction in noise. Because these amplifiers must be kept at a constant temperature, they are usually mounted in insulated boxes which are atuomatically refrigerated or heated. The pump frequency power must be adjustable and constant at any given value; consequently, the oscillator is usually mounted in the temperature stabilized box along with the parametric unit, and the voltages supplies are very carefully regulated. The gain of the unit is kept will below the unstable point (typically 20 db insertion gain).

Where still lower noise temperatures are required, a maser amplifier is used. These amplifiers result in system noise temperatures of about 35° K and give about 7 1/2 db improvement in noise over the parametric amplifier. However, these amplifiers are very sensitive to the bath temperature of the ruby crystal, and their performance deteriorates rapidly when the temperature goes above 4.5° to 5° K. Normally the crystals are in liquid helium which in turn is surrounded by liquid nitrogen. Because liquid helium is not readily available outside of the United States, it was necessary to develop some other means of maintaining the maser at a low temperature. For this purpose a helium closed-cycle refrigerator system has been developed which will maintain a ruby crystal at a temperature of 4.2° K. These units will be used at all our ground tracking stations.

Single-cavity maser amplifiers have bandwidths of 0.5 to 3.0 Mc. Where wider bandwidths are required it is necessary to use a traveling-wave type maser which has a bandwidth of about 15 Mc. Also the gain of single-cavity masers is about 20 db, and where the ultimate in receiver sensitivity is required, it is necessary to use a parametric amplifier between it and the receiver. Traveling wave masers have gains over 30 db, and it is not considered necessary for them to be followed by parametric amplifiers.

Table 6 shows the characteristics of both parametric and maser amplifiers.

Bild (Fig.) 16 is a cutaway diagram of a 960-Mc maser amplifier; Bild (Fig.) 17 shows a maser installed in a cassegrain cone; Bild (Fig.) 18 shows the maser control equipment instrumentation system; and Bild (Fig.) 19 illustrates a parametric amplifier installed near the focal point of an 85-ft antenna.

Table 6. Amplifier characteristics (Ref. 10, 11, 12)

Frequency	960 Mc	2295 Mc
Parametric amplifier		
Gain, normal, db	20	20
Bandwidth, Mc	10	25
Noise temperature, deg K	100-130	130-170
Pump frequency, Gigacycle	17.4	17.4
Temperature, stabilized (ambient -23 to +55° C	30° C	30° C
Maser amplifier	Cavity	T. W.
Gain db	20	36
Bandwidth, Mc (3 db)	0.67	15
Noise temperature, deg K	25	13
Voltage standing wave ratio (input or output)	-	< 1.5

The preamplifier amplifies the energy received from the spacecraft transmitter by the antenna and feeds it to the input of the radio receiver. Automatic phase control receivers are used because they make it possible to use very narrow bandwidths and synchronous detection and still follow gross freqency change due to doppler, etc. The receiver is usually a two-stage superheterodyne with the phase of the local oscillator automatically adjusted to be in quadrature with the phase of the input signal. RF outputs from the receiver are used to detect the doppler frequency by comparison with station-generated reference frequencies, to detect angle error signals coherently for controlling the pointing of the antenna and to detect telemetry and range code modulation of the RF carrier (Ref. 7). Particular care is taken to provent RF leakage and cross talk between receiver components and other station equipment.

Due to the loss that would be incurred in trying to carry the modulated RF carrier from the antenna feed over several hundred feet of coaxial cable to the first mixer in the receiver, the preamplifier and the first stage of the receiver are mounted on the antenna. If the feed is at the antenna focal point, the preamplifier and mixer equipment are located at the apex of the feed quadrapod. If a cassegrain system is used, the preamplifier is mounted in the cassegrain cone, and the mixer is either mounted there or in a box or rack fastened to the back of the reflector. No frequency higher than ϕ 150 Mc is carried from the antenna to the receiver in the control room. Bild (Fig.) 20 illustrates a 960 Mc receiver mounted in a rack in a tracking station.

Table 7 gives the basic characteristics of a 960-Mc phase-lock receiver.

3.4 Data Acquisition

One of the prime purposes of a tracking and data acquisition station is to receive and record telemetry data from the spacecraft, by recording on magnetic tape the detected output of the receiver and forwarding this tape record to a centralized data

Table 7. Characteristics of a 960-Mc phase-lock receiver (Ref. 9)

Nominal center frequency	960 Mc
Automatic frequency tracking range	
Strong signal levels	± 26 kc
Threshold signal levels	± 2.6 kc
Automatic phase control effective noise bandwidth at threshold	20 or 60 cps
Effective system noise temperature*	
Parametric preamplifier	200°K
Maser and parametric preamplifier	50°K
Threshold carrier level (phase lock cannot be maintained) BW = 20 cps	
Parametric amplifier	-162 dbm
Maser and parametric amplifier	-167 dbm
Maximum frequency tracking rate BW = 20 cps	
Strong signal level (30 deg phase error)	336 cpsps
Threshold signal level (6 deg phase error)	5.8 cpsps
Dynamic signal level range	-50 dbm to threshold
Static gain error over dynamic signal level range	6 db max
Intermediate frequencies	
First	30 Mc
Second	455 kc
Intermediate frequency amplifier half power bandwidths	
First	2 Mc
Second	2 kc

*Includes receiver, transmission line, feed and antenna pointing at quiet sky.

processing center where the data is separated, collated, and referenced to calibration signals and made available for analysis. However, in order to compute midcourse and terminal maneuver requirements and to watch over the condition of the spacecraft, it is necessary to select certain telemetry signals and send them immediately to the operations center. This is done by installing at each station demodulation and decommutation equipment which is especially designed to match the type of modulation and commutation being used on the spacecraft. After decommutation the selected telemetry signals are encoded in teletype code and transmitted by teletype to the operations center.

Besides the detected signal from the receiver, basic station data is also recorded on the magnetic tape. This includes such items as receiver static and dynamic phase error, signal strength, automatic gain control voltage, acquisition relay signal, command signals (if any), Greenwich mean time signals, wow and flutter tones, and voice label. Analog pen or photographic recorders are used to record special data for use by station personnel or for later data analysis.

When the communications system is designed to use standard IRIG FM telemetry, discriminators with standard channel-selector filters are used to separate the telemetry data. When these are used it is customary to record on the magnetic tape the frequency of the voltage-controlled oscillators in the discriminators. The magnetic tape recorders have the following characteristics:

Speed: 1 7/8 to 60 ips (6 speeds)
Tape width: 1/2 in.
Tape reels: 10-1/2 or 14 in.
Flutter: 0.3% peak to peak cumulative from DC to 10,000 cps
Tracks: 7

Frequency response: 300 to 250,000 cps - ±3 db at 60 ips

Type recording: direct, FM, or pulse deviation.

For special projects such as television pictures etc., it is sometimes necessary to be able to record a very wide band of frequencies. In these instances special recording facilities such as video tape recorders or television monitors with photographic cameras are used. The video tape recorder may be used to record the receiver intermediate frequency directly before detection. This may be done when it is desired to eliminate any possibility of loss of telemetry information in the detection process. Special precautions must be taken with the recording of PCM data on video recorders in order not to lose code synchronization. Bild (Fig.) 21 is a view of a typical deep space station telemetry and recording equipment.

3.5 Tracking

A second important purpose of a tracking and data acquisition station is to track a spacecraft so that its position in space will be known. This is accomplished at the ground station by measuring the angular position of the antenna with respect to certain reference directions when it is pointing at the spacecraft, by determining the relative velocity between the Earth and the spacecraft by measuring the doppler frequency, and by measuring the range or distance between the spacecraft and the Earth. The antenna position is determined by two digital angle resolvers that are driven by the two antenna-bearing shafts. These angles are measured to a resolution of 0.002 deg. On polar-mount antennas the hour angle is measured westward from the celestial meridian with 270 deg being east, and the declination angle is measured north or south of the celestial equator with positive declinations being in the northern hemisphere. On Az-El mount antennas the azimuth angle is measured eastward from true north with 90 deg being east, and the elevation angle is measured upwards from the horizon with 90 deg being the zenith.

To obtain accurate doppler measurements it is usual to instrument the spacecraft so that its transmitted frequency is coherent with and has a fixed ratio with respect to its received frequency. For our L-band frequencies this ratio is 89/96; that is, the spacecraft transmitted frequency is a nominal 960 Mc and its received frequency is 890 Mc. In the ground station the transmitter exciter obtains its basic frequency from a stable, spectrally pure oscillator, usually an atomic standard, so that any effect on the doppler frequency due to oscillator variations during the time required for radio transmission from Earth to spacecraft and return is minimized. The two-way doppler frequency is the difference between the ground transmitter carrier frequency and the received carrier frequency multiplied by the reciprocal of the ratio of the spacecraft transmitted to received frequencies. Neglecting higher order and relativistic terms, the velocity of the spacecraft away from the Earth is equal to: (Ref. 13)

$$V = \frac{DC}{2F-D}$$

where

D = two-way doppler frequency
F = ground transmitter carrier frequency
C = velocity of light

In actual practice the doppler frequency is measured with respect to a frequency lower than the carrier frequency, usually one of the IF frequencies, and is then multiplied back up to a frequency approximately that of the transmitted carrier. The accuracy of the measured doppler frequency is primarily dependent upon the spacecraft velocity, the time period of counting the doppler frequency and the multiplying factor. Using multiplying factors of 30 and a 1-min sample period, our usual effective noise is 0.02 cps which is equivalent, at L-band frequencies, to about 0.003 m/sec.

Ranging may be accomplished in several different ways, but basically it is a measurement of the time it takes for an electromagnetic wave to travel from the ground station to the spacecraft and return. In our system we make use of the cross-correlation properties of certain binary wave forms to determine this time unambiguously to planetary distances. The binary wave form is a pseudorandom code whose period is greater than the total round trip propagation time but which is generated by synchronously combining sets of short separately acquirable codes to make it possible to determine the correlation point in a very small percentage of the total code period. The coded binary waveform phase modulates the transmitter carrier, is transponded back to the ground receiver by the spacecraft, where it is cross-correlated with a like code generated at the receiver. Our present design uses 1-μsec digit periods whose relative positions can be detected to 1/2 of a μsec, which corresponds to a range resolution of 75 meters. However, by also comparing relative phase shifts between the transmitted and received carriers it is possible to improve this resolution to about 1.25 meters. The actual range accuracy is on the order of ±15 meters and is heavily dependent upon our knowledge of the velocity of radio waves in space (Ref. 7).

The antenna angular position signals, the doppler frequencies, and the ranging signals are combined with signals which represent the day of the year, the Greenwich mean time of day in hours, minutes, and seconds, and a signal which represents the condition of the data. The combined digitally encoded signals are converted to standard Baudot 5-hole teletype code in the automatic data handling equipment and are punched out on paper tape at rates up to 60 characters per second. The contents of this type are periodically transmitted by teletype to the operations control center where the information is used to compute the spacecraft's trajectory.

Bild (Fig.) 22 is a picture of a typical automatic data handling equipment installation.

3.6 Command and Control

The third important function of a deep space tracking and data acquisition station is that of command and control. The accuracies required of probes which are designed to explore the Moon, planets, and deep space are such that midcourse and terminal maneuvers are necessary. This is done by transmitting signals to the spacecraft which will initiate roll, pitch, and yaw turns and propulsion ignition and timing to an amount calculated from tracking measurements. It is also necessary to send signals to the spacecraft to perform such functions as will either prevent damage or improve reliability, will correct malfunctions, change data rates, change the type of telemetry information being transmitted, turn the transmitter on or off or change its power, reorient the spacecraft or antenna, or change antennas. The spacecraft receiver is usually instrumented to receive coded command signals, to direct them to the command signal decoder, and to either institute immediate action or to store the command for future action. We presently use a binary coded command signal with a work length which varies according to mission requirements and which is transmitted at a rate of one bit per second.

It is important that incorrect or false commands are not transmitted because of the possibility of damaging the spacecraft or its mission. To help prevent this from happening, "read-write-verify" units are installed at each station. When a command has been selected, it is sent three separate times by teleprinter to the station where the message is read into the read-write-verify unit and compared and verified. During the RF transmission to the spacecraft a monitor receiver detects a portion of the RF signal and compares the transmitted command bit by bit with the command displayed and stored in the read-write-verify unit. Transmission is inhibited if an error is detected. If a command is stored in the spacecraft, it is usually telemetered back to the transmitting station so that the actual received command can be compared with the correct one. We customarily design the command channel to have a bit error probability of 10^{-5} or less, so as to minimize the possibilities of errors in the RF transmission link (Ref. 12).

Bild (Fig.) 23 is a picture of a read-write-verify unit.

3.7 Power

Due to the remote locations of deep space stations, primary power is usually obtained from diesel motor generator units. These units produce 60-cycle, 3-phase current which is reduced by transformers to the distribution voltages of 115/208 volts. It is desirable to have separate units furnish power for electrical equipment and for station housekeeping functions such as heating, air conditioning, and lighting so that sudden load changes will not transmit transients to the sensitive receiving and transmitting equipment. It is also necessary to have back-up power units for maintenance purposes and for use in case of a failure.

The normal complement for a station with an 85-ft antenna, is four 150 kw diesel generator sets.

Motor generator sets are used to furnish 400 cycle power to the 10 kw transmitters.

4. ~~SYSTEM CAPABILITIES~~ OPERATIONS CONTROL

The capabilities of a space communications system is a complicated matter which is heavily related to the design of the spacecraft communications components. For example, it may be desirable, because of reliability and other factors, to use a directional antenna on an attitude-controlled spacecraft which is not movable with respect to the spacecraft structure. Such a design is feasible for certain trajectories, provided the antenna pattern can be made to give sufficient gain throughout the cruise period, and provided the maximum gain will be available at the time of encounter with the planet. Although this design is feasible, it may require the ground station to use its maximum capabilities over long periods of time. The overall system reliability is therefore the result of ~~both the spacecraft design and~~ the design and operational capabilities of the ground station, and the resultant compromises and tradeoffs must be carefully calculated and considered in order to achieve maximum results.

Due to the general deep space communication requirement of low noise levels, it is desirable to select frequencies which will have the minimum natural and man-made noises. As noted in Bild (Fig.) 15, the galactic noise increases rapidly below about 1 gigacycle, and atmospheric noise increases above about 10 gigacycles. Deep space frequencies therefore generally will be between these two values. Frequencies now being used are 890 Mc Earth-to-space and 960 Mc space-to-Earth. However, equipment developments indicate improved capabilities can be accomplished through the use of 2290-2300 Mc space-to-Earth and 2110-2120 Earth-to-space frequencies, and equipment is now being procured to change over to these frequencies by 1965. The use of higher frequencies, e.g. X-band (8,000 Mc), awaits an evaluation of the capabilities of equipment components ~~at these frequencies~~.

The operations control of spacecraft during launch, midcourse and terminal maneuvers and during emergencies caused by nonstandard operations ~~requires~~ is performed at a single operations center. At this center are located the deep space ground stations network operations control center, computing facilities for calculating trajectories and look angles, project or mission control personnel, a communications center, and data reduction and processing equipment. The ground stations send to this center their recordings of data received from the spacecraft both by teletype and by mail for rapid analysis of spacecraft condition and for future data reduction. For the center to perform its function of operations control it is necessary to have communications lines, both voice and teletype, to the ground stations. The voice lines are usually temporary and are used during launch and maneuver operations. Commercial telephone facilities are used when possible, but other special purpose facilities are also used if available. The teletype lines are leased commercial circuits and are

Table 8. Tracking network capabilities

Number of stations	3
Number of 85-ft antennas	4
Tracking rate, max	0.7 deg per sec
Pointing error, max	0.1 deg
Angle data	Digitally encoded
Angular resolution	0.002 deg
Drive system	Hydrostatic multimotored, multispeed servo-valve controlled
Type of feed	Tracking, simultaneous lobing
Polarization	Right circular
System noise temperature, Goldstone	50° K
System noise temperature, Woomera, South Africa	200° K
Receiver	Phase lock
Receiver frequency	955-965 Mc
Phase-lock loop BW	20 or 60 cps nominal
First IF frequency and bandwidth	30 Mc, 1-2 Mc
Second IF frequency and bandwidth	455 kc, 1600 or 5000 cps
Transmitter power	10 kw
Transmitter frequency	890 Mc
Two-way doppler accuracy (60 sec intervals)	0.003 m/sec
Data recorders	1/2 in. magnetic tape
Analog recorders	36 channel photographic
Power	4-150 kw diesel generators

operational 24 hours per day. Where transmission conditions are difficult it is usual to have more than one routing available. Bild (Fig.) 24 shows a diagram of the communications network presently being used by the DSIF.

Before communications can be established with a spacecraft the ground station must "acquire" it. This means that the antenna must be so positioned that the spacecraft is in the main antenna beam, and the receiver must be tuned to the received frequency. Fortunately for deep space exploration, the location and frequency of a spacecraft are accurately known after only a few days of tracking, and the spacecraft can be acquired easily even when the received signal strength approaches receiver threshold. In order to aid acquisition in the period immediately following launch, each station is equipped with a small, wide-beam tracking antenna which is mounted on the big antenna. When smooth tracking is accomplished with the small antenna, operational control is switched to the large antenna.

Table 8 shows the basic system capabilities of a deep space tracking network.

5. THE DEEP SPACE INSTRUMENTATION FACILITY

The general requirements and capabilities of a deep space ground station and network have been described. The Deep Space Instrumentation Facility which was constructed to meet the requirements for tracking, commanding, controlling and receiving data from deep space probes launched by the United States National Aeronautics and Space Administration is a good example of how these requirements and capabilities have been implemented into a practical working system. This facility has successfully tracked and received data from spacecraft that were launched into normal and abnormal trajectories. It has also demonstrated its long-range capabilities over a five-month period by daily tracking and obtaining data from Mariner II until it passed Venus at a distance of 36 million miles from Earth.

The DSIF will be continually updated and improved as new equipment and components are developed and engineered so that it will maintain a state-of-the-art capability. Present plans for improving the deep space communications system, which includes both the DSIF and the spacecraft, are based on new equipment designs, circuits, and modulation methods which will, in a period of about ten years, increase the information capability by over one billion times.

The DSIF consists of three stations; Johannesburg, South Africa; Woomera, Australia; and Goldstone, United States. Pictures of these three stations are shown in Bild (Fig.) 25, 26, 27 and 28.

Literature

1. K. W. Linnes, W. D. Merrick, and R. Stevens: Ground Antenna for Space Communication System. IRE Transactions of the Professional Group on Space Electronics and Telemetry. Vol Set-6, No. 1, March, 1960

2. E. Rechtin: Basic Constraints of Space Communications, Lecture No. 2 in Space Communications. A. V. Balakrishnan, editor. McGraw Hill Book Co. 1962, pg. 4.

3. P. D. Potter: Design of Antennas for Space Communications. JPL informal publication.

4. E. Rechtin, B. Rule, and R. Stevens: Large Ground Antennas. Technical Report 32-213, Jet Propulsion Laboratory, Pasadena, California, March 20, 1962.

5. D. C. Hogg: Effective Antenna Temperatures, Due to Oxygen and Water Vapor in the Atmosphere. Journal of Applied Physics, Vol. 30, No. 9, September, 1959.

6. C. W. Allen: Paper No. 45, International Astronomical Union Symposium No. 4 on Radio Astronomy. August, 1955, Cambridge University Press, pg. 254.

7. R. P. Mathison: Tracking Techniques for Interplanetary Spacecraft. Technical Memorandum 33-88, Jet Propulsion Laboratory, Pasadena, California, May 21, 1962.

8. Space Program Summary, No. 37-14, vol. I. Jet Propulsion Laboratory, Pasadena, California, April 1, 1962. pgs. 53-62.

9. Space Program Summary, No. 37-22, vol. III. Jet Propulsion Laboratory, Pasadena, California. July 31, 1963. pgs. 10-11.

10. Space Program Summary, No. 37-11, vol. I. Jet Propulsion Laboratory, Pasadena, California. Oct. 1, 1961. pg. 61.

11. Deep Space Net System Specification. Technical Memorandum 33-26. Jet Propulsion Laboratory, Pasadena, California. July, 1960. Section II. B. 4.

12. B. D. Martin: The Mariner Planetary Communication System Design. Jet Propulsion Laboratory Technical Memo 33-88, May 21, 1962.

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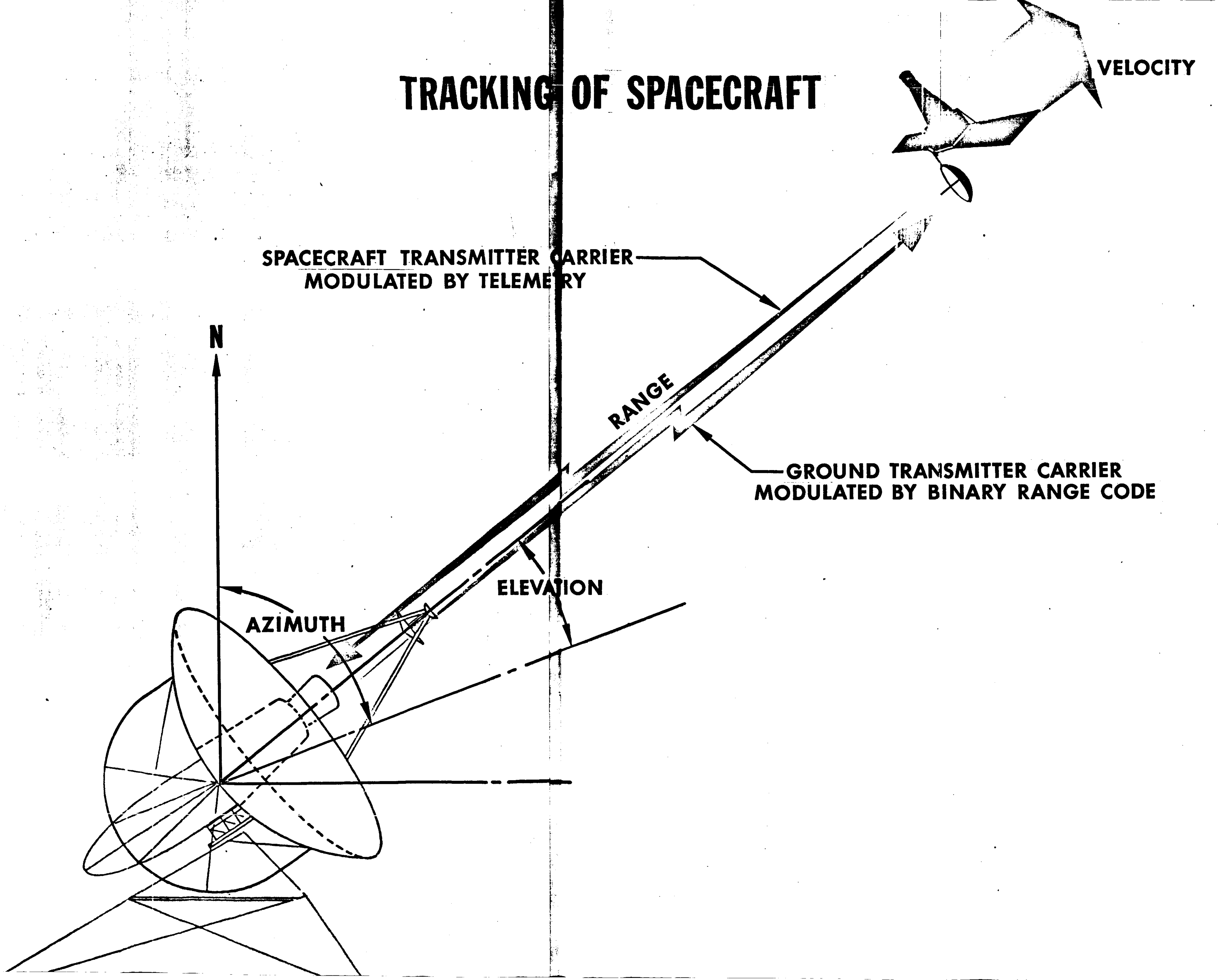
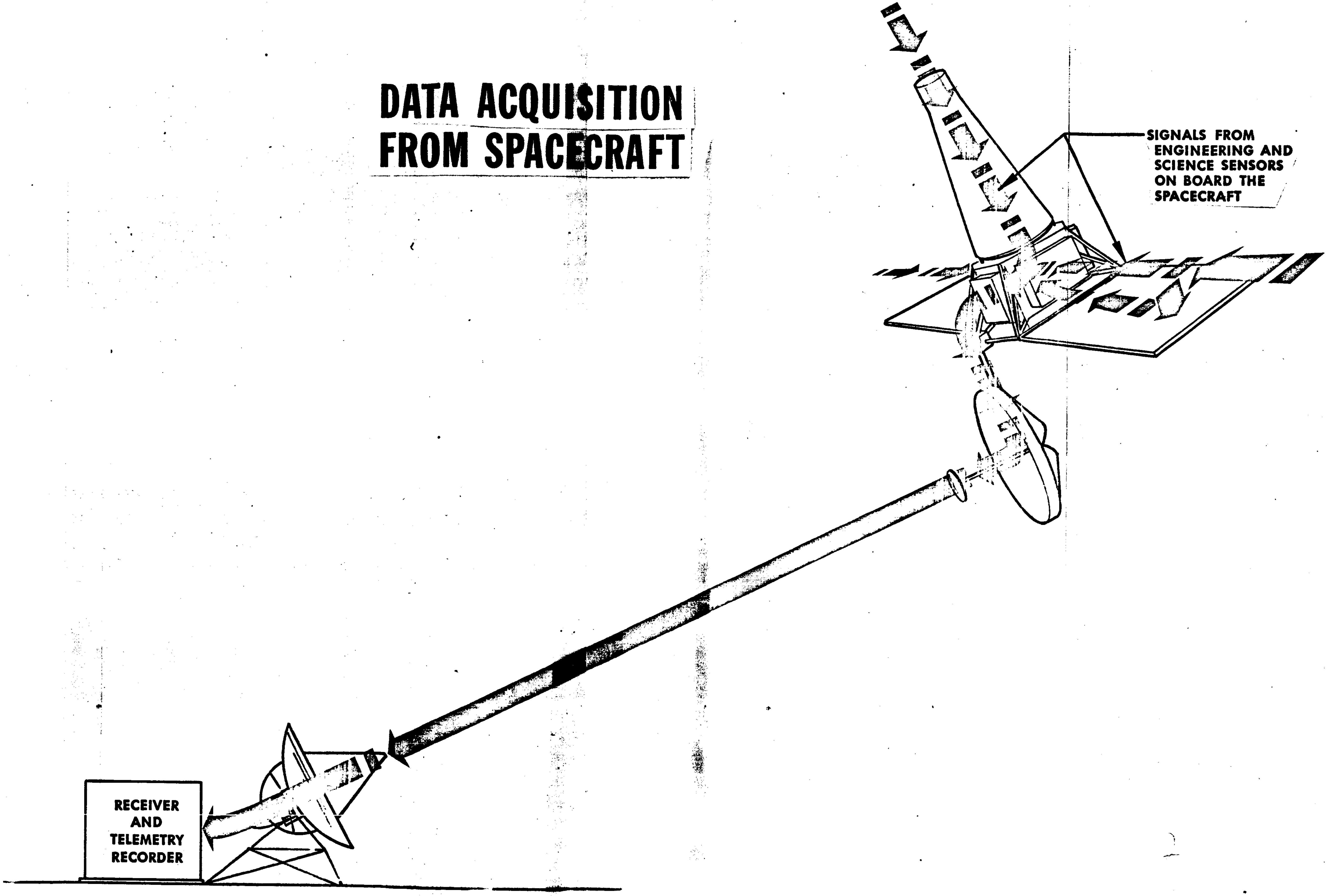
FIGURES

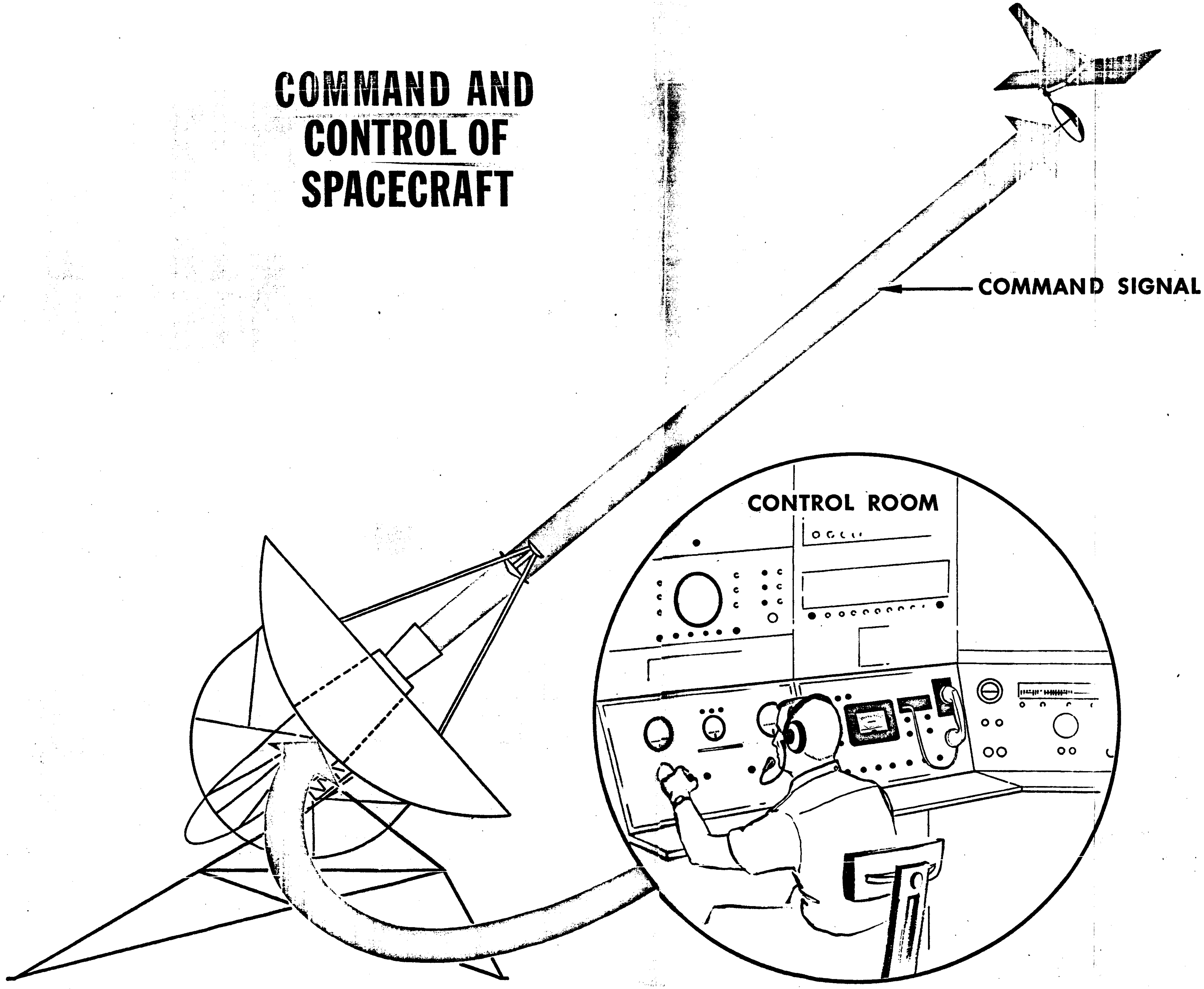
TRACKING OF SPACECRAFT



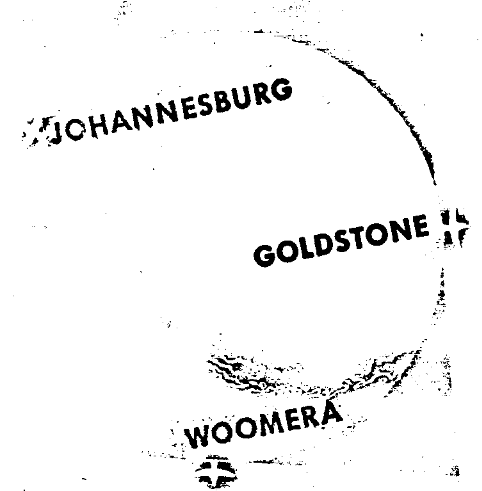
DATA ACQUISITION FROM SPACECRAFT



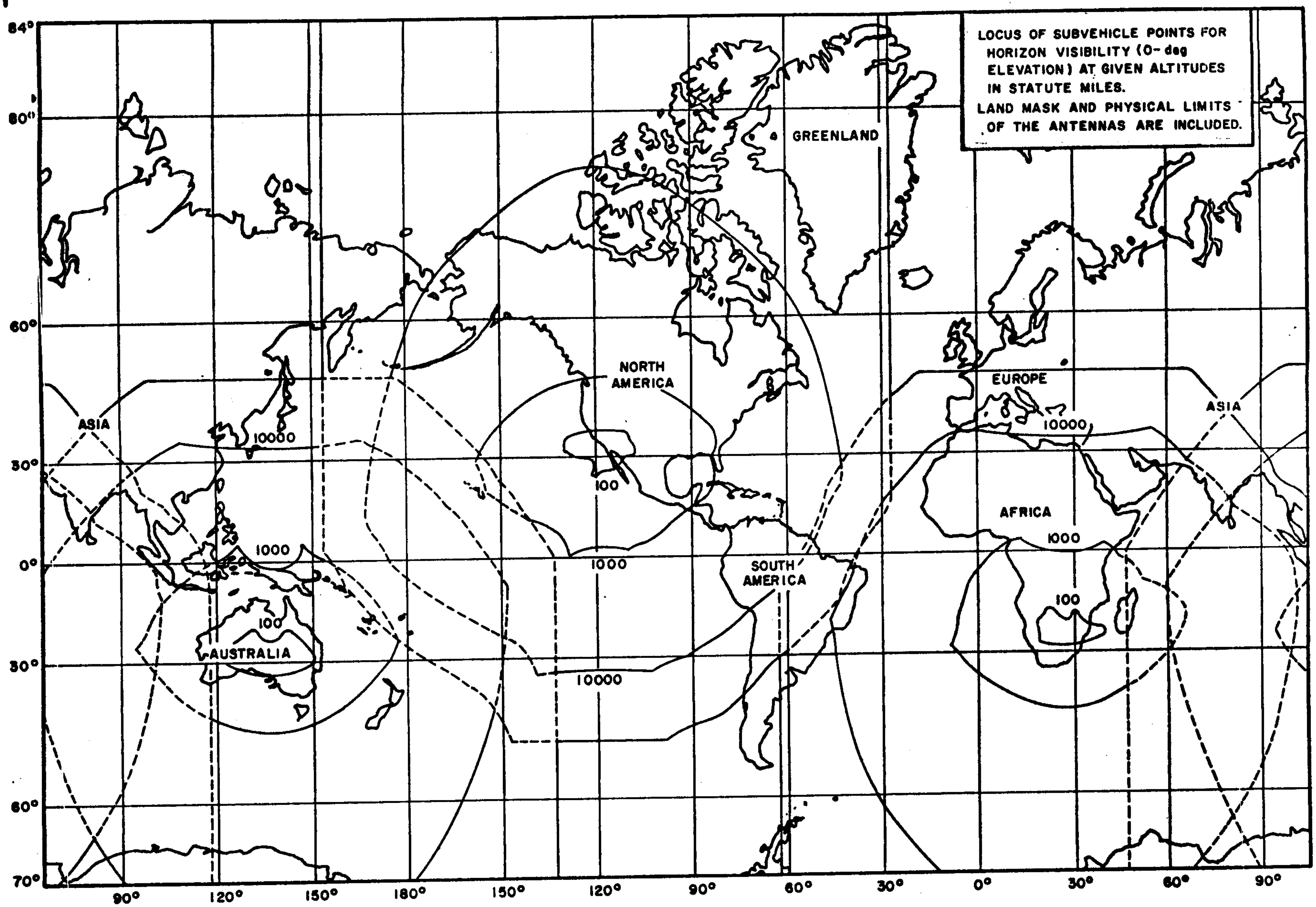
COMMAND AND CONTROL OF SPACECRAFT



DEEP SPACE NETWORK STATION VISIBILITIES

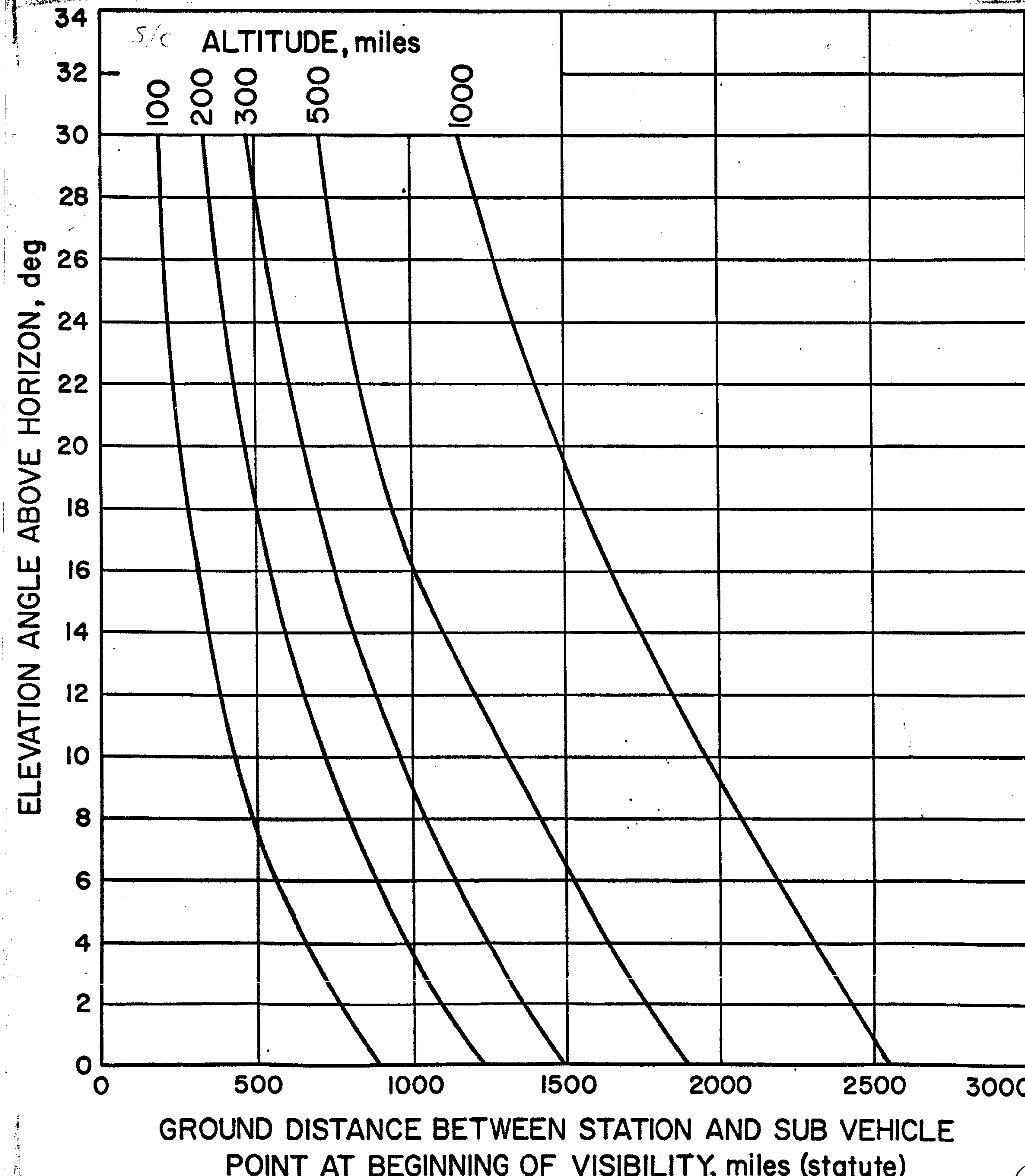


VII-1

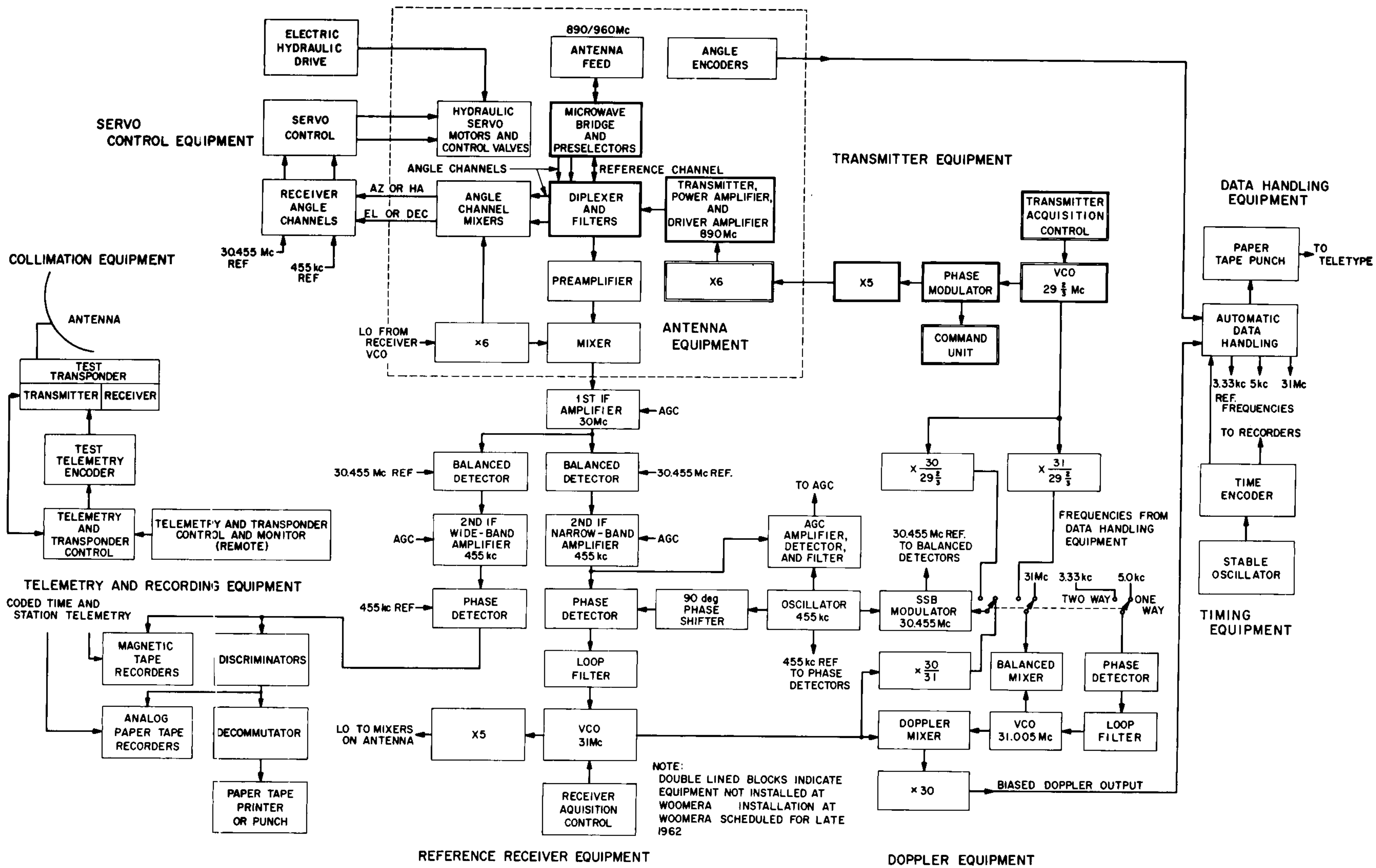


LOCUS OF SUBVEHICLE POINTS FOR HORIZON VISIBILITY (0-deg ELEVATION) AT GIVEN ALTITUDES IN STATUTE MILES.
LAND MASK AND PHYSICAL LIMITS OF THE ANTENNAS ARE INCLUDED.
GREENLAND
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
ASIA
ASIA
AUSTRALIA
10000
1000
100
10000
1000
100
10000
1000
100
84°
80°
60°
30°
0°
30°
60°
70°
90°
120°
150°
180°
150°
120°
90°
60°
30°
0°
30°
60°
90°

9 × 6 1/8



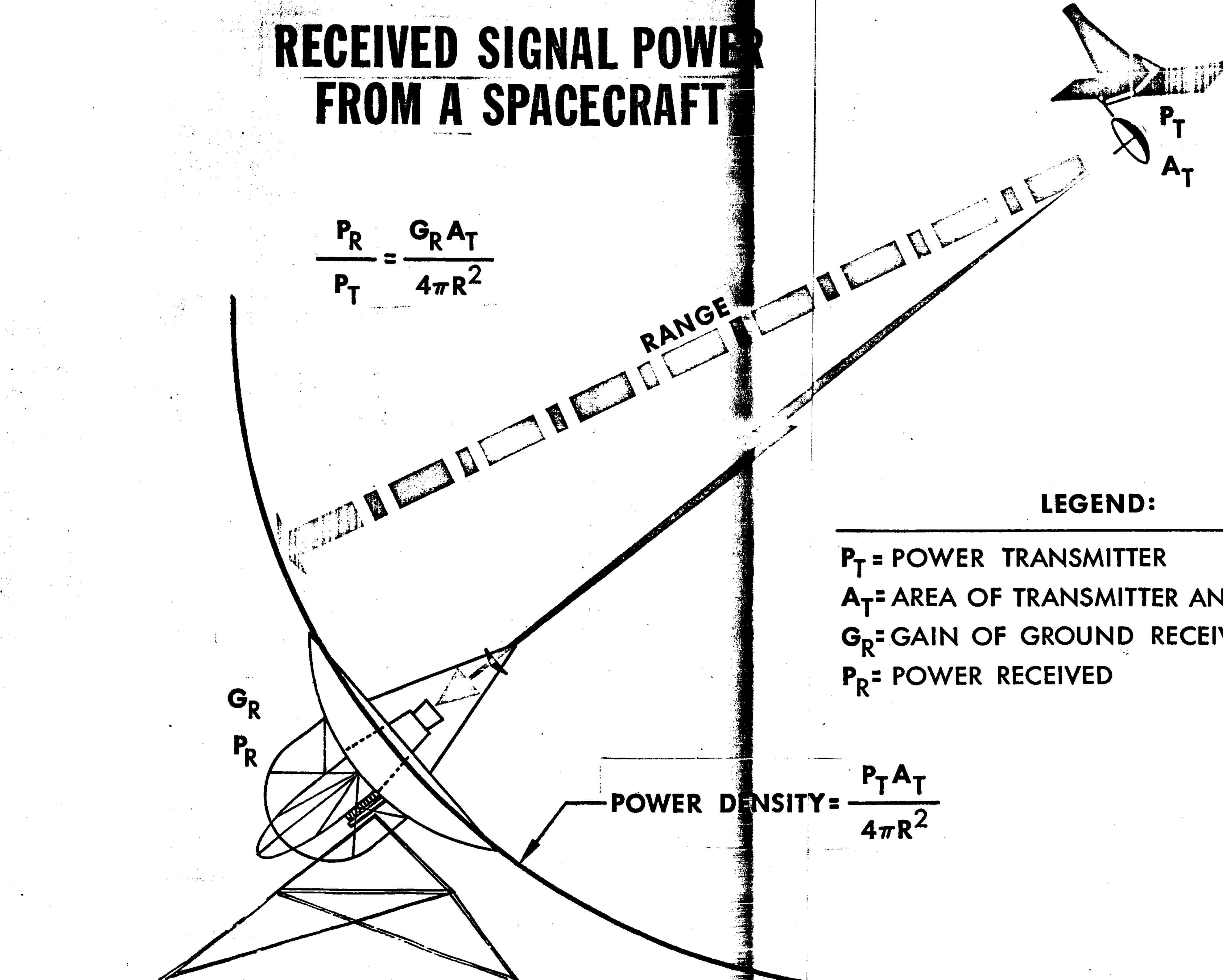
S/C
ALTITUDE, miles
100
200
300
500
1000
ELEVATION ANGLE ABOVE HORIZON, deg
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
500
1000
1500
2000
2500
3000
GROUND DISTANCE BETWEEN STATION AND SUB VEHICLE POINT AT BEGINNING OF VISIBILITY, miles (statute)



SERVO CONTROL EQUIPMENT
ELECTRIC HYDRAULIC DRIVE
SERVO CONTROL
RECEIVER ANGLE CHANNELS
30.455 Mc REF
455 kc REF
HYDRAULIC SERVO MOTORS AND CONTROL VALVES
ANGLE CHANNEL MIXERS
AZ OR HA
EL OR DEC
ANGLE CHANNELS
REFERENCE CHANNEL
890/960Mc
ANTENNA FEED
MICROWAVE BRIDGE AND PRESELECTORS
DIPLEXER AND FILTERS
PREAMPLIFIER
MIXER
×6
LO FROM RECEIVER VCO
ANGLE ENCODERS
TRANSMITTER, POWER AMPLIFIER, AND DRIVER AMPLIFIER 890Mc
X6
ANTENNA EQUIPMENT
TRANSMITTER EQUIPMENT
X5
PHASE MODULATOR
COMMAND UNIT
VCO 29 2/3 Mc
TRANSMITTER ACQUISITION CONTROL
DATA HANDLING EQUIPMENT
PAPER TAPE PUNCH
TO TELETYPE
AUTOMATIC DATA HANDLING
3.33kc 5kc 31Mc REF. FREQUENCIES
TO RECORDERS
TIME ENCODER
STABLE OSCILLATOR
TIMING EQUIPMENT
COLLIMATION EQUIPMENT
ANTENNA
TEST TRANSPONDER
TRANSMITTER
RECEIVER
TEST TELEMETRY ENCODER
TELEMETRY AND TRANSPONDER CONTROL
TELEMETRY AND TRANSPONDER CONTROL AND MONITOR (REMOTE)
TELEMETRY AND RECORDING EQUIPMENT
CODED TIME AND STATION TELEMETRY
MAGNETIC TAPE RECORDERS
DISCRIMINATORS
ANALOG PAPER TAPE RECORDERS
DECOMMUTATOR
PAPER TAPE PRINTER OR PUNCH
1ST IF AMPLIFIER 30Mc
AGC
BALANCED DETECTOR
30.455 Mc REF
30.455 Mc REF.
2ND IF WIDE-BAND AMPLIFIER 455 kc
2ND IF NARROW-BAND AMPLIFIER 455 kc
PHASE DETECTOR
455 kc REF
LOOP FILTER
VCO 31Mc
X5
LO TO MIXERS ON ANTENNA
RECEIVER AQUISITION CONTROL
REFERENCE RECEIVER EQUIPMENT
90 deg PHASE SHIFTER
OSCILLATOR 455 kc
455 kc REF TO PHASE DETECTORS
AGC AMPLIFIER, DETECTOR, AND FILTER
TO AGC
SSB MODULATOR 30.455Mc
30.455 Mc REF. TO BALANCED DETECTORS
$\times \frac{30}{29\frac{2}{3}}$
$\times \frac{31}{29\frac{2}{3}}$
FREQUENCIES FROM DATA HANDLING EQUIPMENT
31Mc 3.33kc 5.0kc
TWO WAY
ONE WAY
$\times \frac{30}{31}$
BALANCED MIXER
PHASE DETECTOR
DOPPLER MIXER
VCO 31.005 Mc
LOOP FILTER
× 30
BIASED DOPPLER OUTPUT
DOPPLER EQUIPMENT
NOTE:
DOUBLE LINED BLOCKS INDICATE EQUIPMENT NOT INSTALLED AT WOOMERA INSTALLATION AT WOOMERA SCHEDULED FOR LATE 1962

RECEIVED SIGNAL POWER FROM A SPACECRAFT

$$\frac{P_R}{P_T} = \frac{G_R A_T}{4\pi R^2}$$



POWER DENSITY = $\frac{P_T A_T}{4\pi R^2}$

LEGEND:

P_T = POWER TRANSMITTER
A_T = AREA OF TRANSMITTER ANTENNA
G_R = GAIN OF GROUND RECEIVING ANTENNA
P_R = POWER RECEIVED

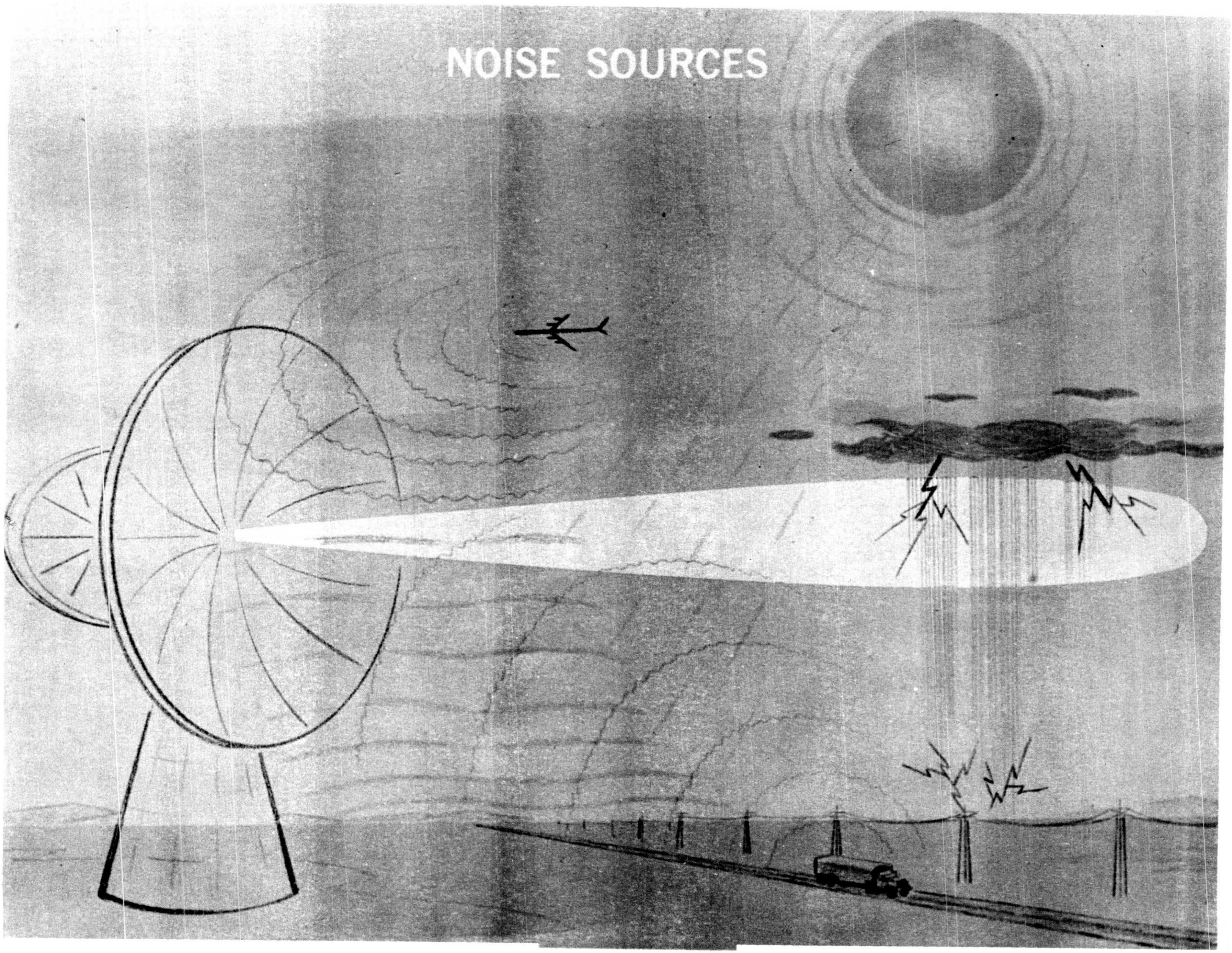
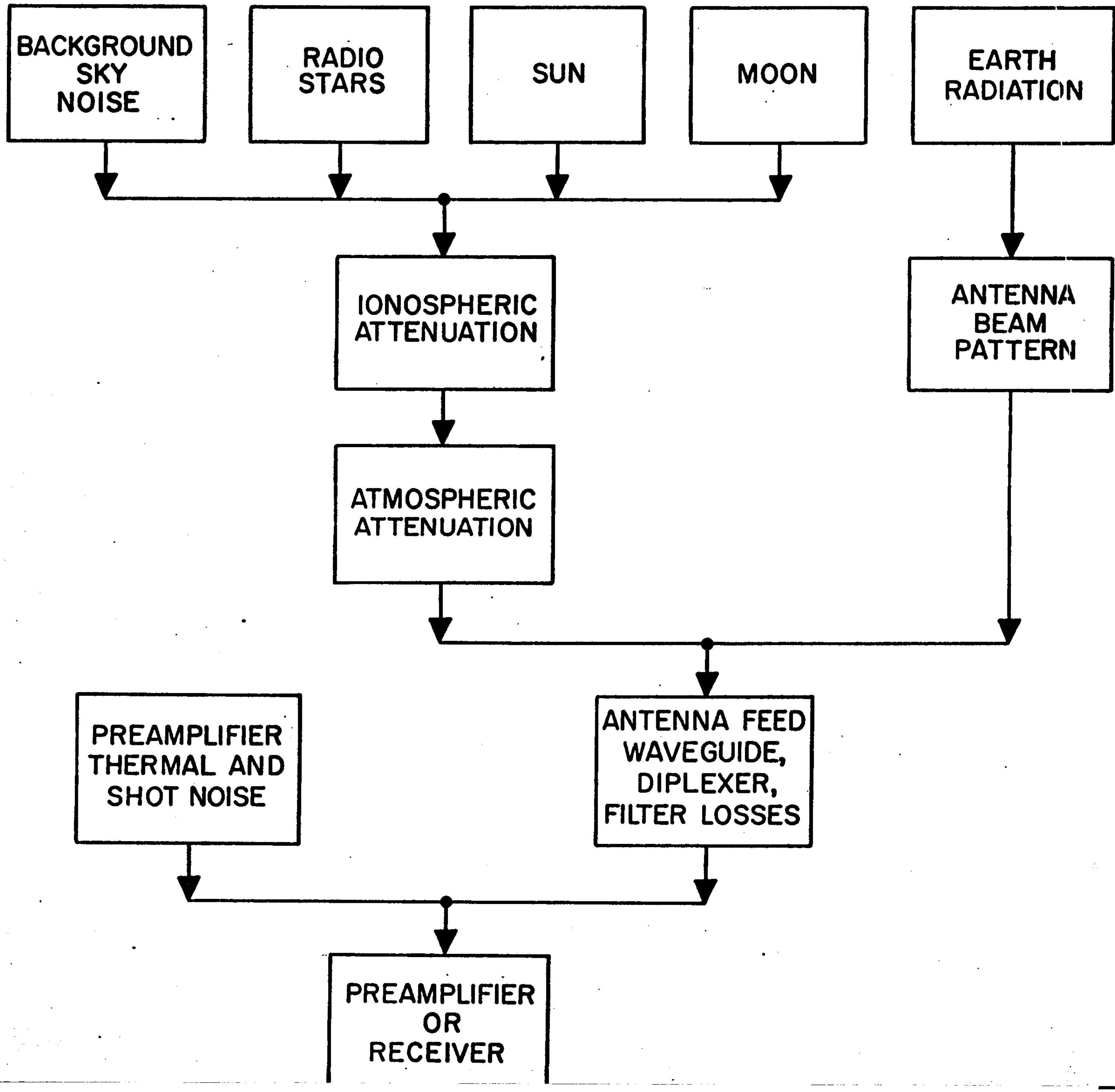


Figure ~~7~~ 13

EQUIVALENT PREAMPLIFIER NOISE CIRCUIT



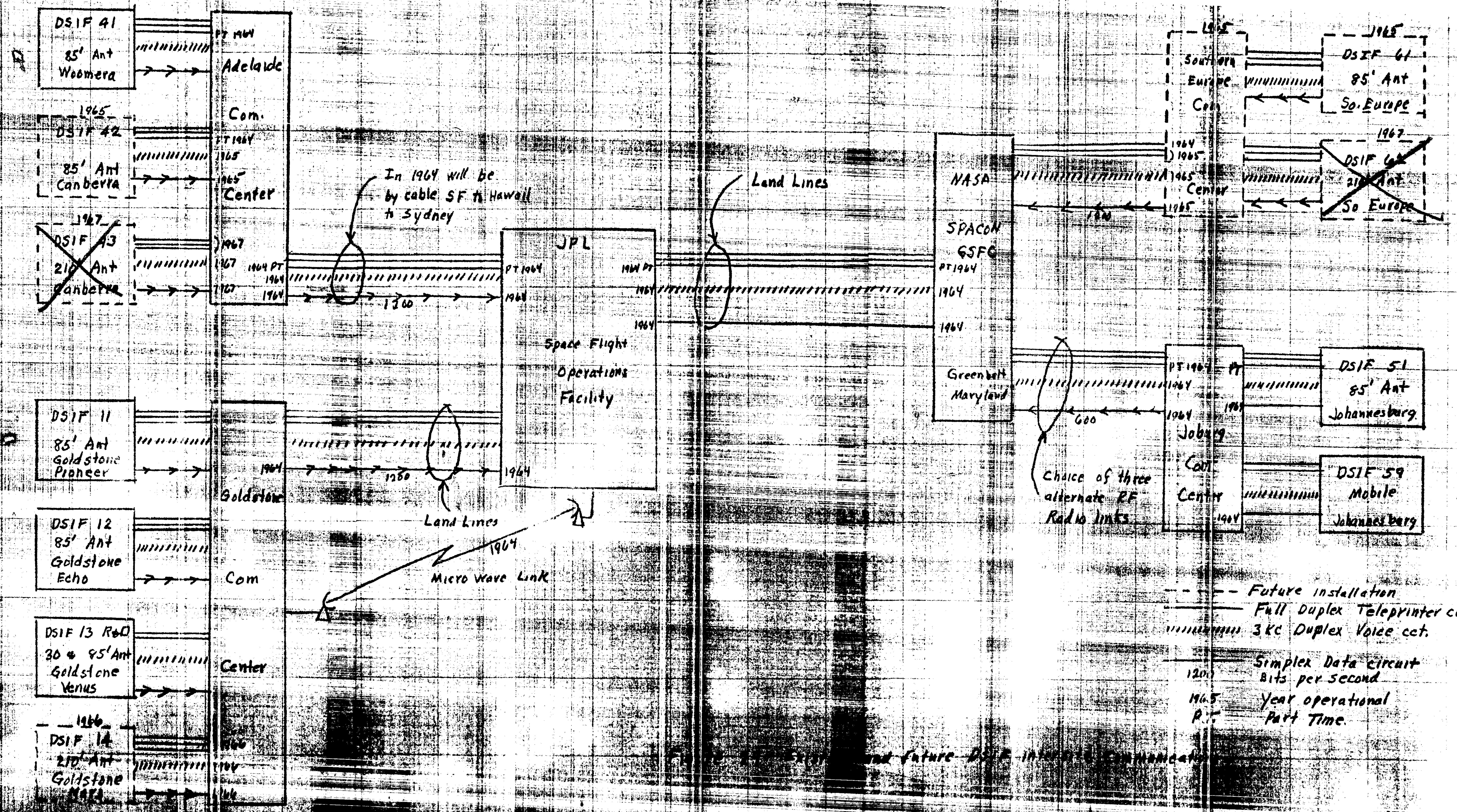
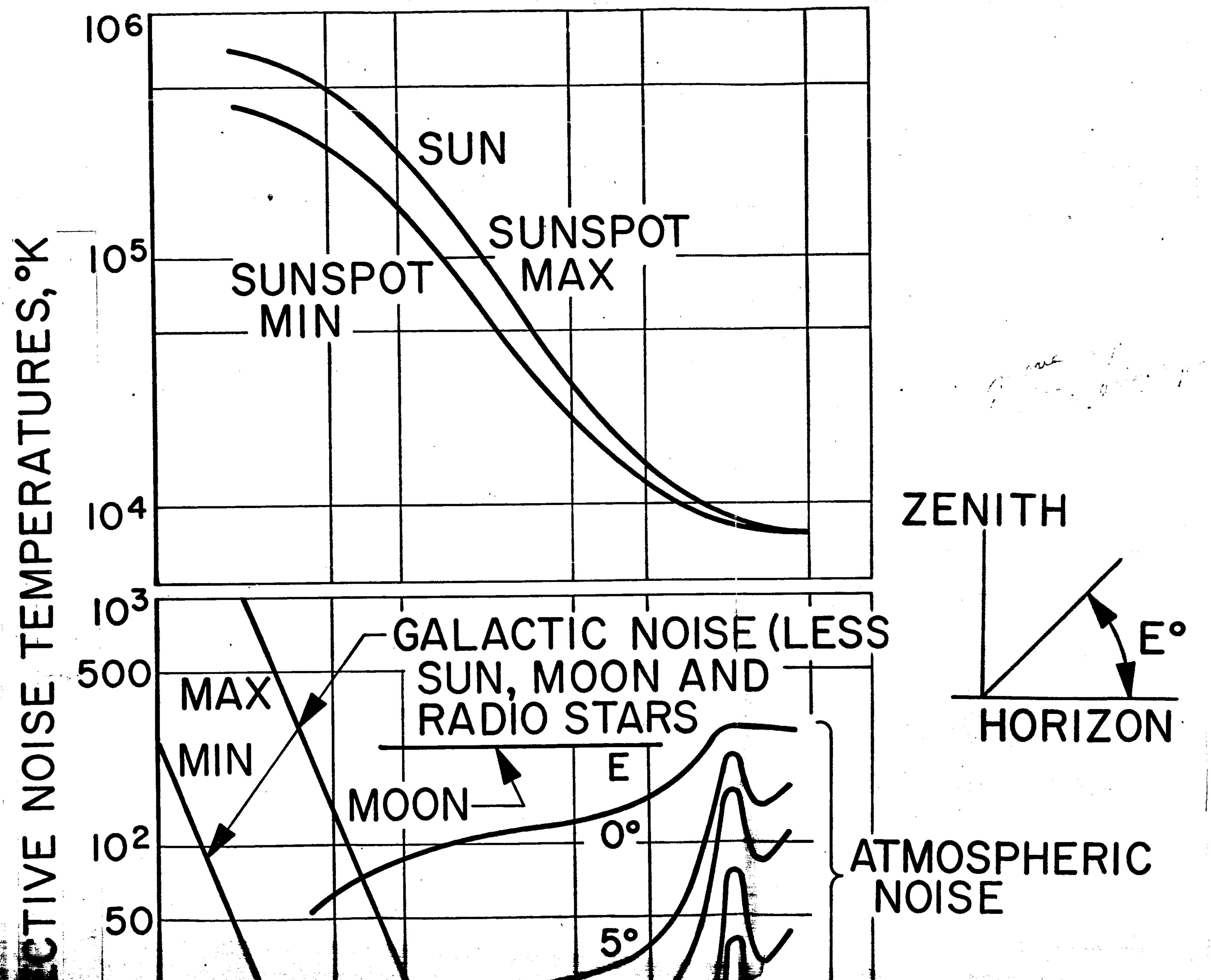
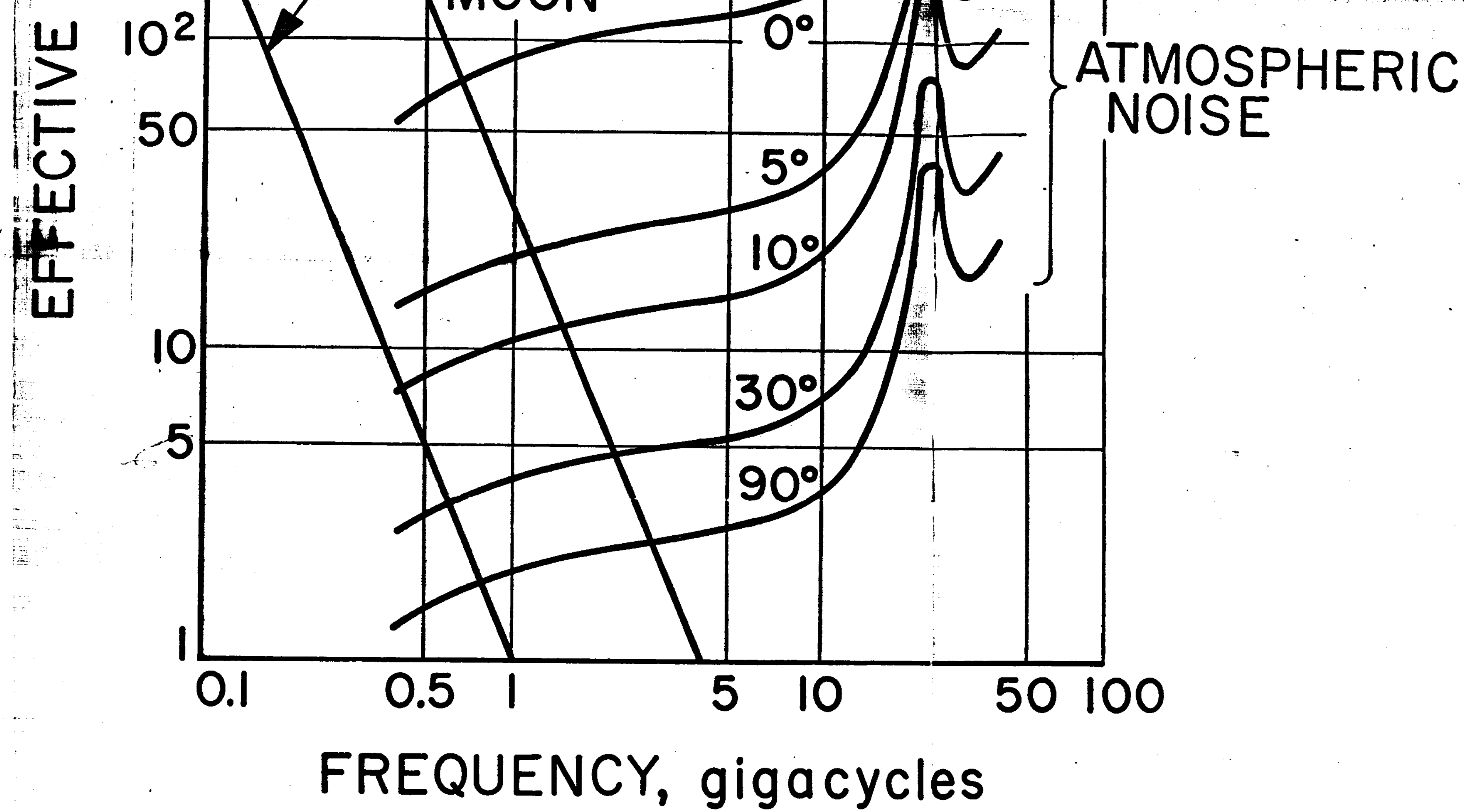


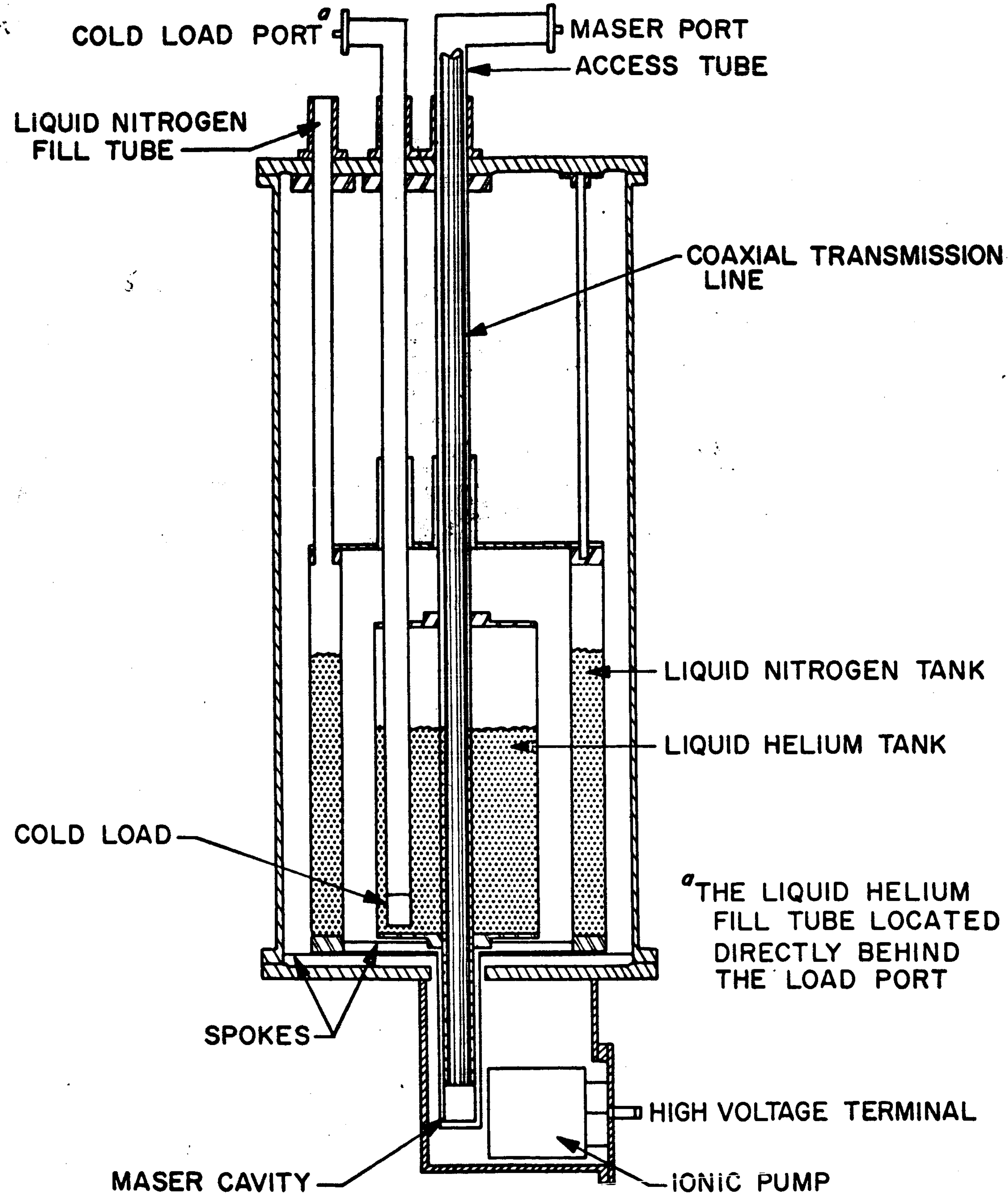
Figure [illegible] and future DSIF [illegible]



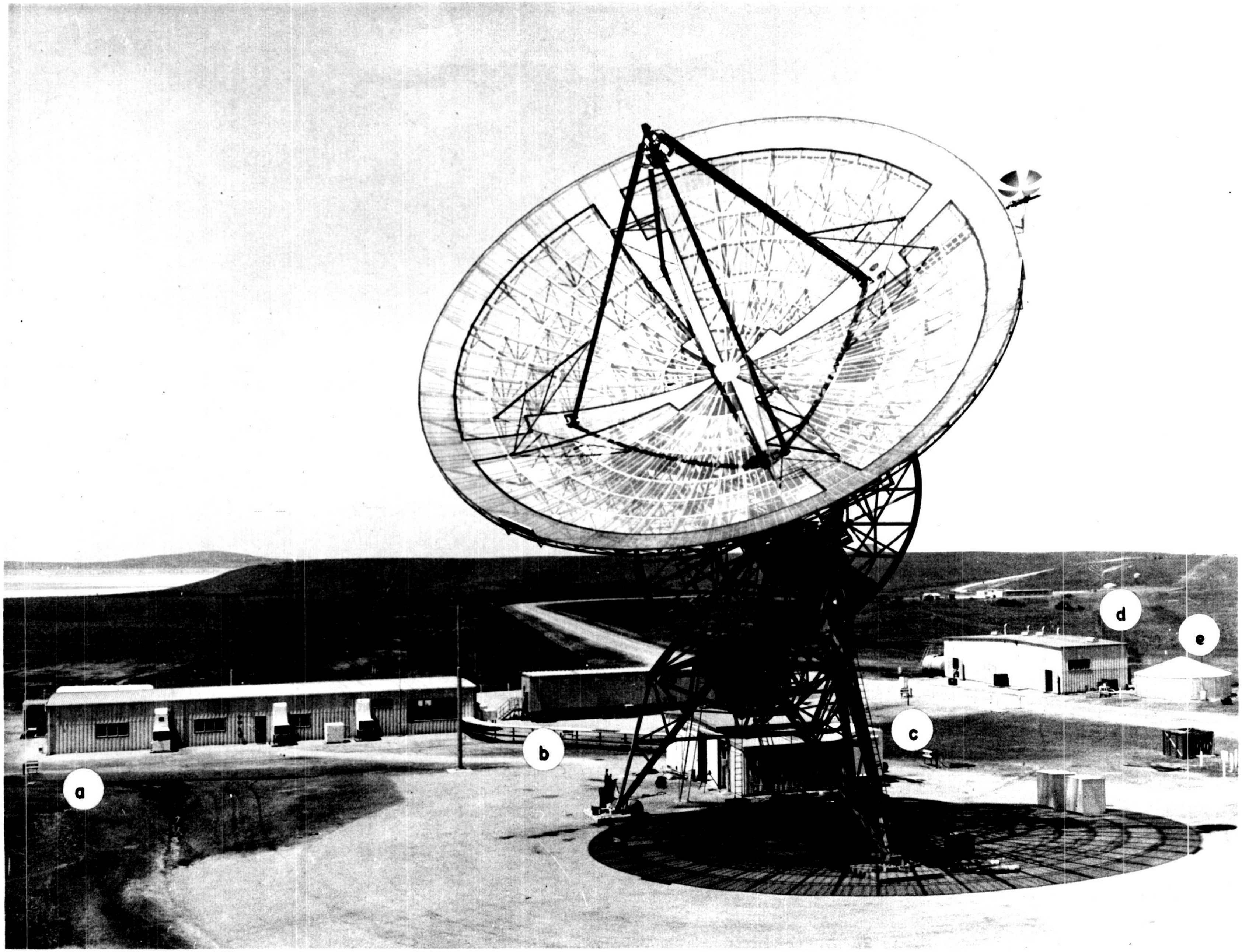
CTIVE NOISE TEMPERATURES, °K
10^6
10^5
10^4
10^3
500
10^2
50
SUN
SUNSPOT MAX
SUNSPOT MIN
ZENITH
E°
HORIZON
GALACTIC NOISE (LESS SUN, MOON AND RADIO STARS
MAX
MIN
MOON
E
0°
5°
ATMOSPHERIC NOISE



GALACTIC AND ATMOSPHERIC NOISE TEMPERATURES
(APPARENT SURFACE BRIGHTNESS FOR THE MOON AND THE SUN)
(REF 7 AND 8)


COLD LOAD PORT[a]
MASER PORT
ACCESS TUBE
LIQUID NITROGEN FILL TUBE
COAXIAL TRANSMISSION LINE
LIQUID NITROGEN TANK
LIQUID HELIUM TANK
COLD LOAD
[a]THE LIQUID HELIUM FILL TUBE LOCATED DIRECTLY BEHIND THE LOAD PORT
SPOKES
HIGH VOLTAGE TERMINAL
MASER CAVITY
IONIC PUMP

960-mc maser



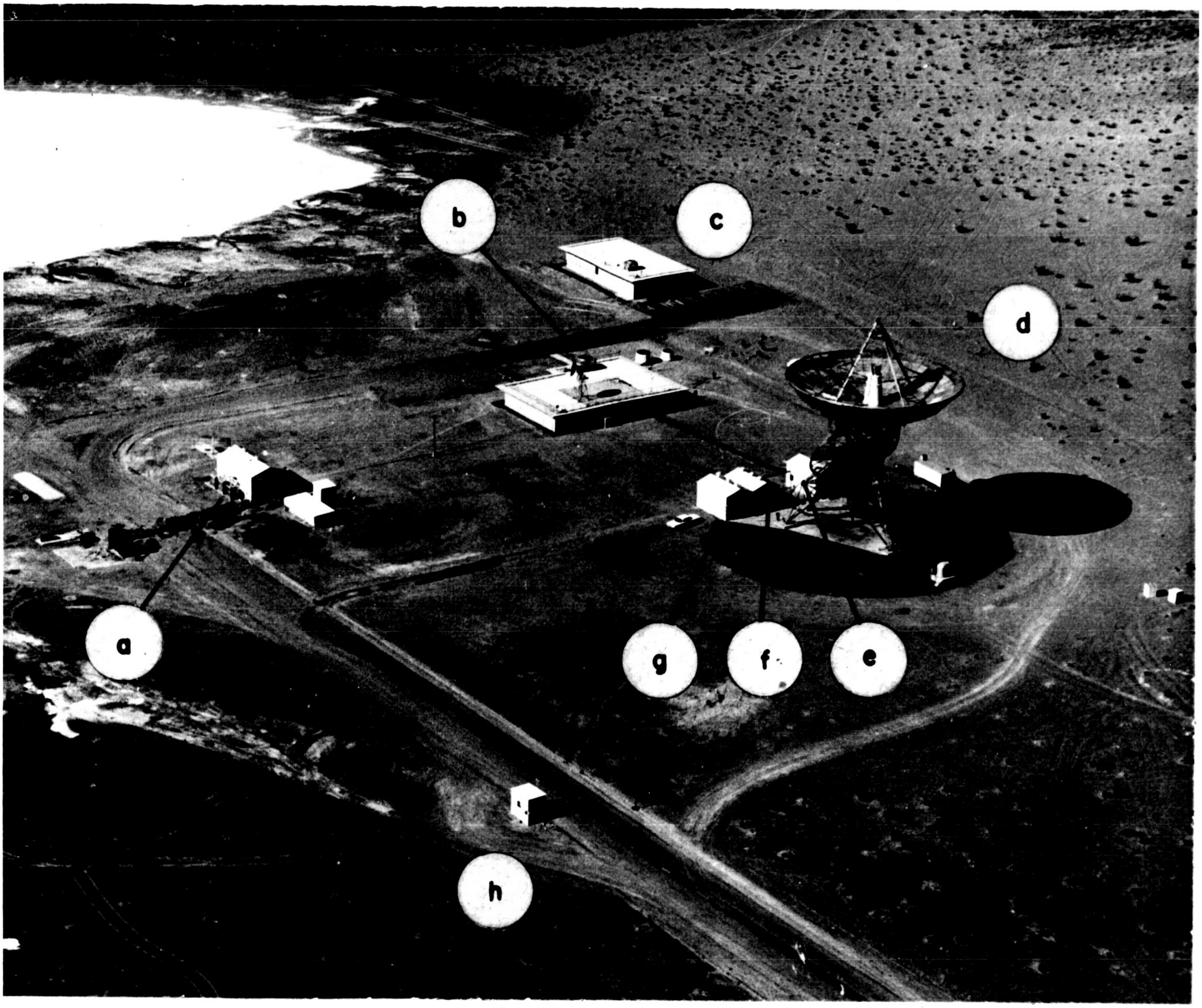
a. CONTROL BLDG

b. TRAILER SHED

c HYDRO-MECHANICAL BLDG

d. GENERATOR BLDG

e. WATER TANK



a. GENERATOR BLDG

b. CONTROL BLDG

c. LABORATORY BLDG

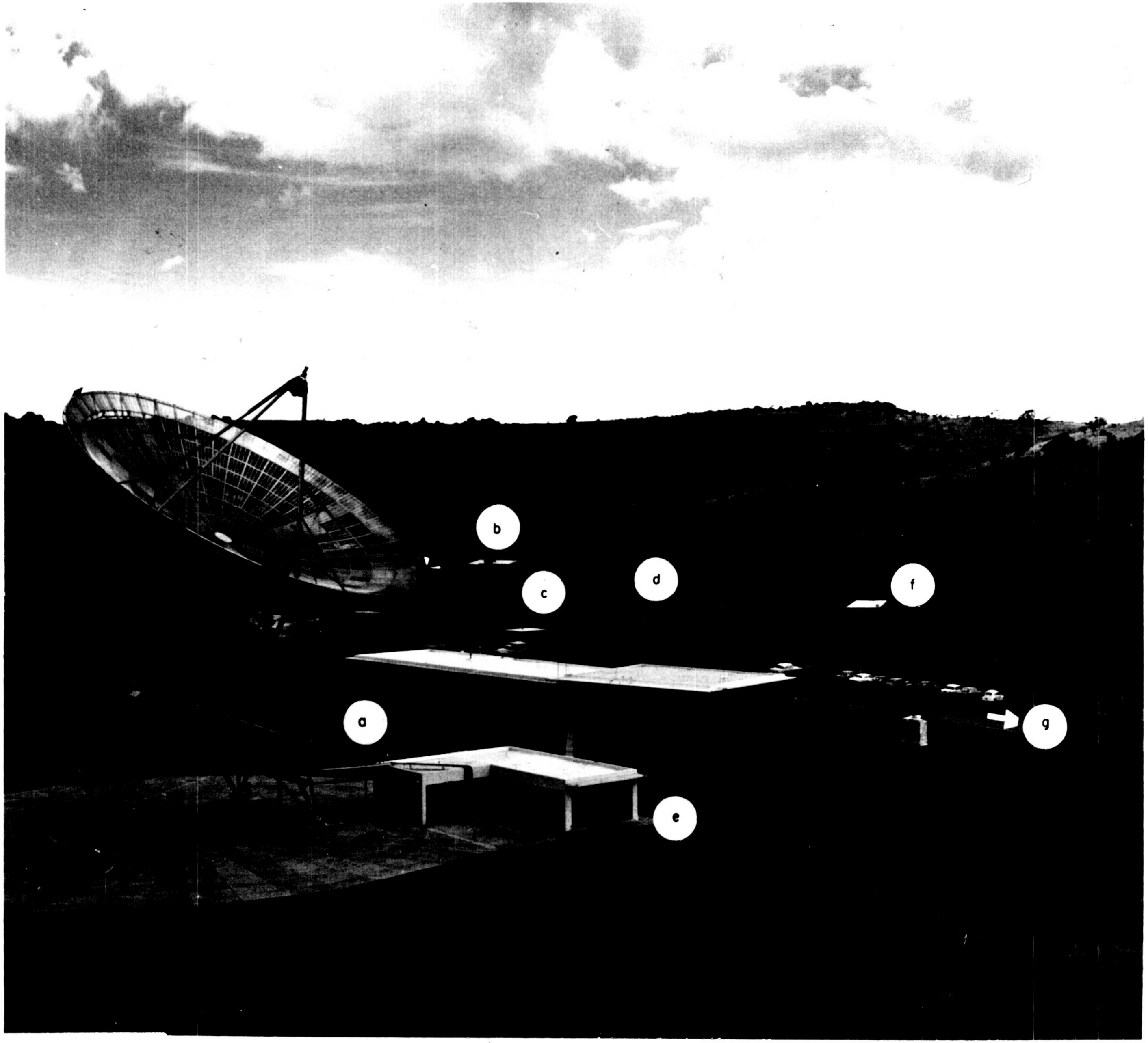
d. ANTENNA

e. HYDRO-MECHANICAL BLDG

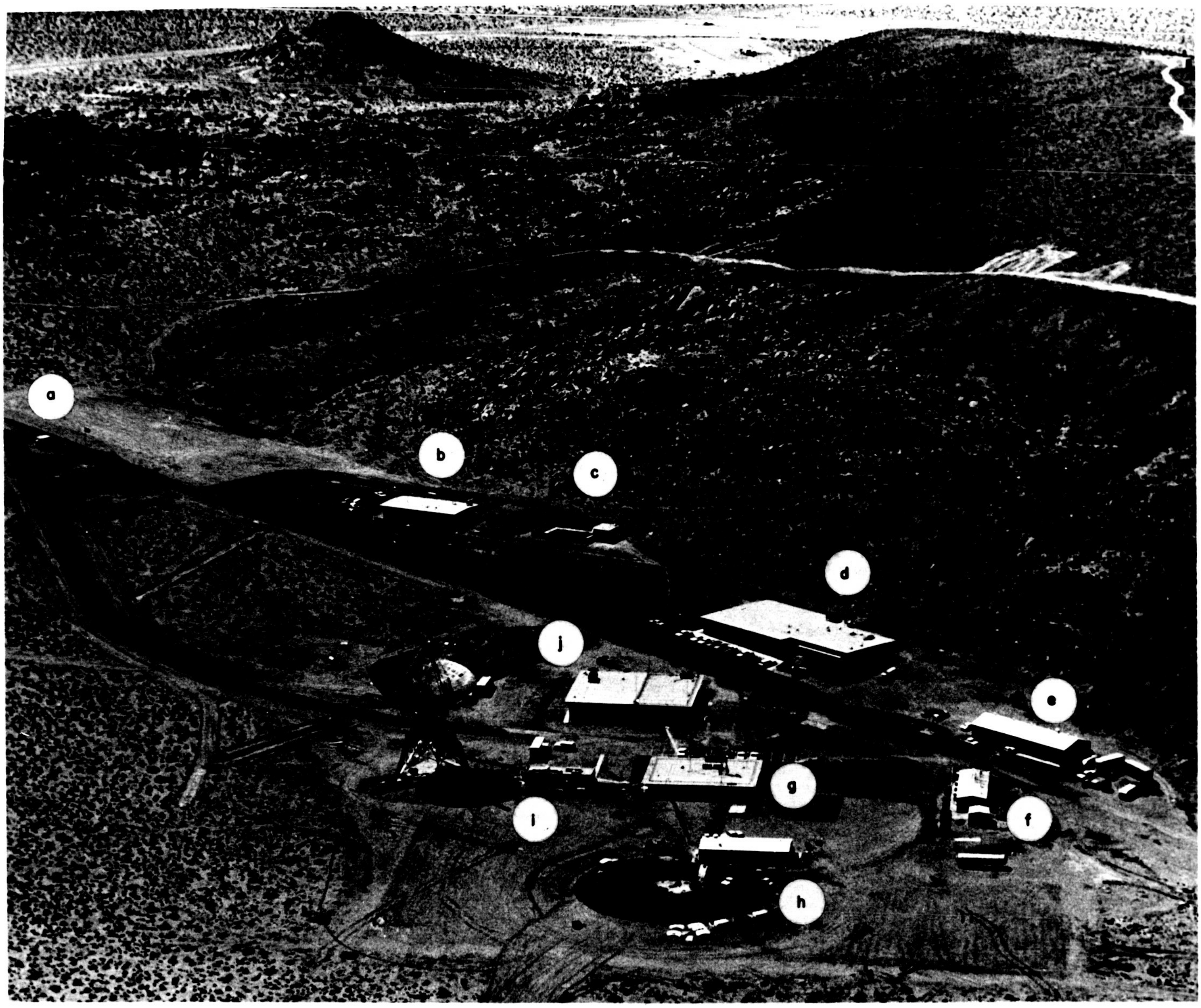
f. MASER AND PARAMETRIC AMPLIFIER BLDG

g. ANTENNA FEED STORAGE BLDG

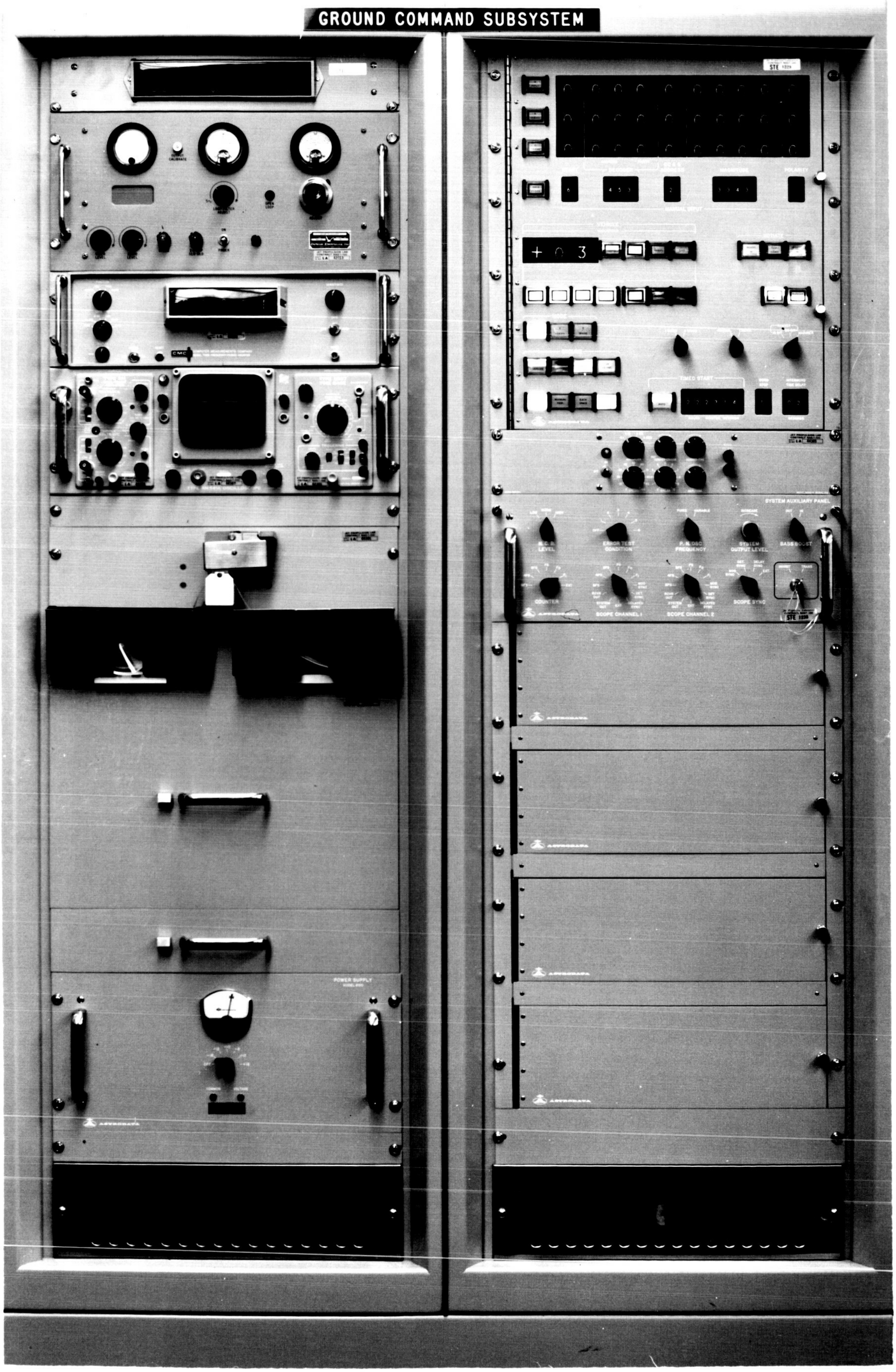
h. GUARD HOUSE

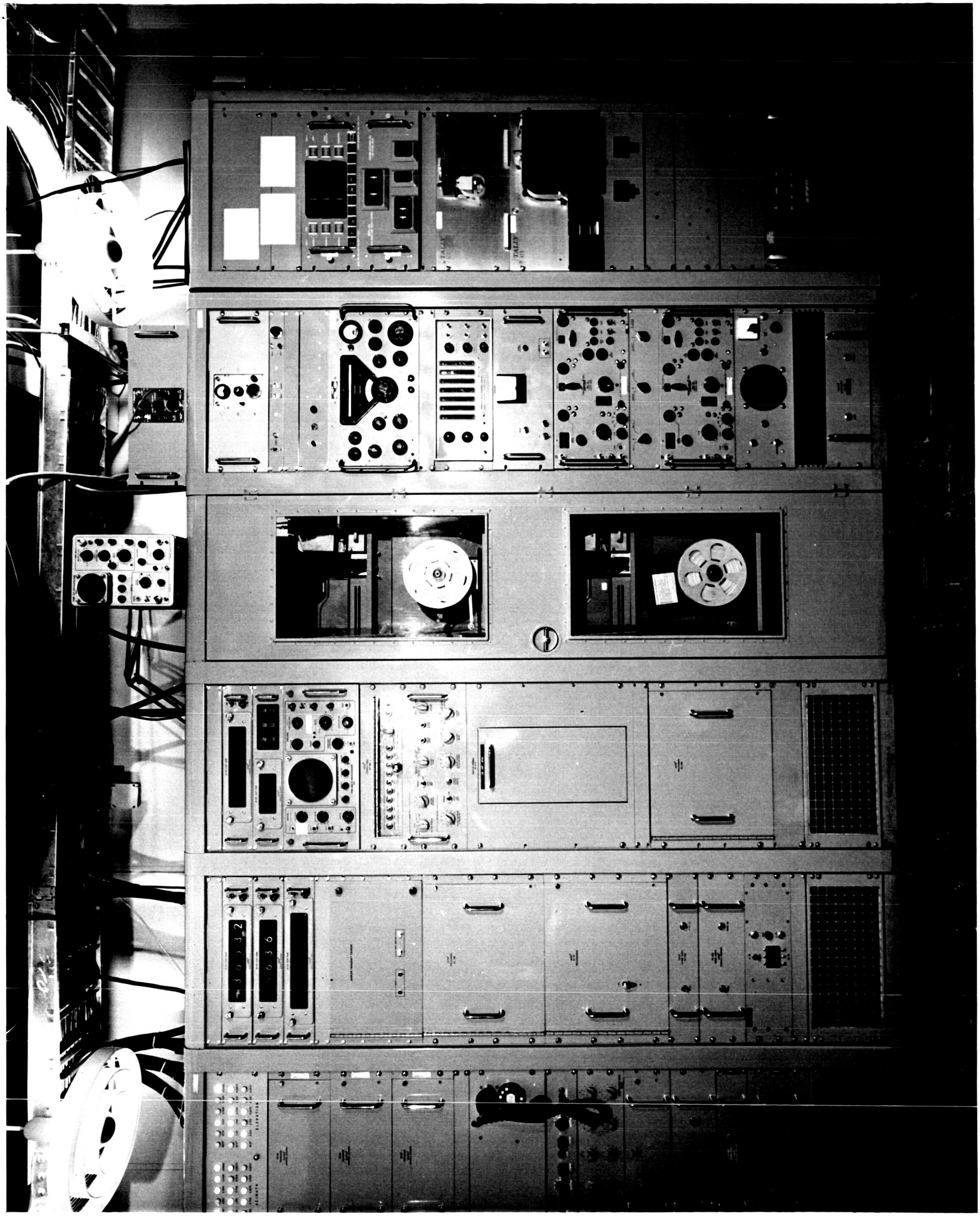


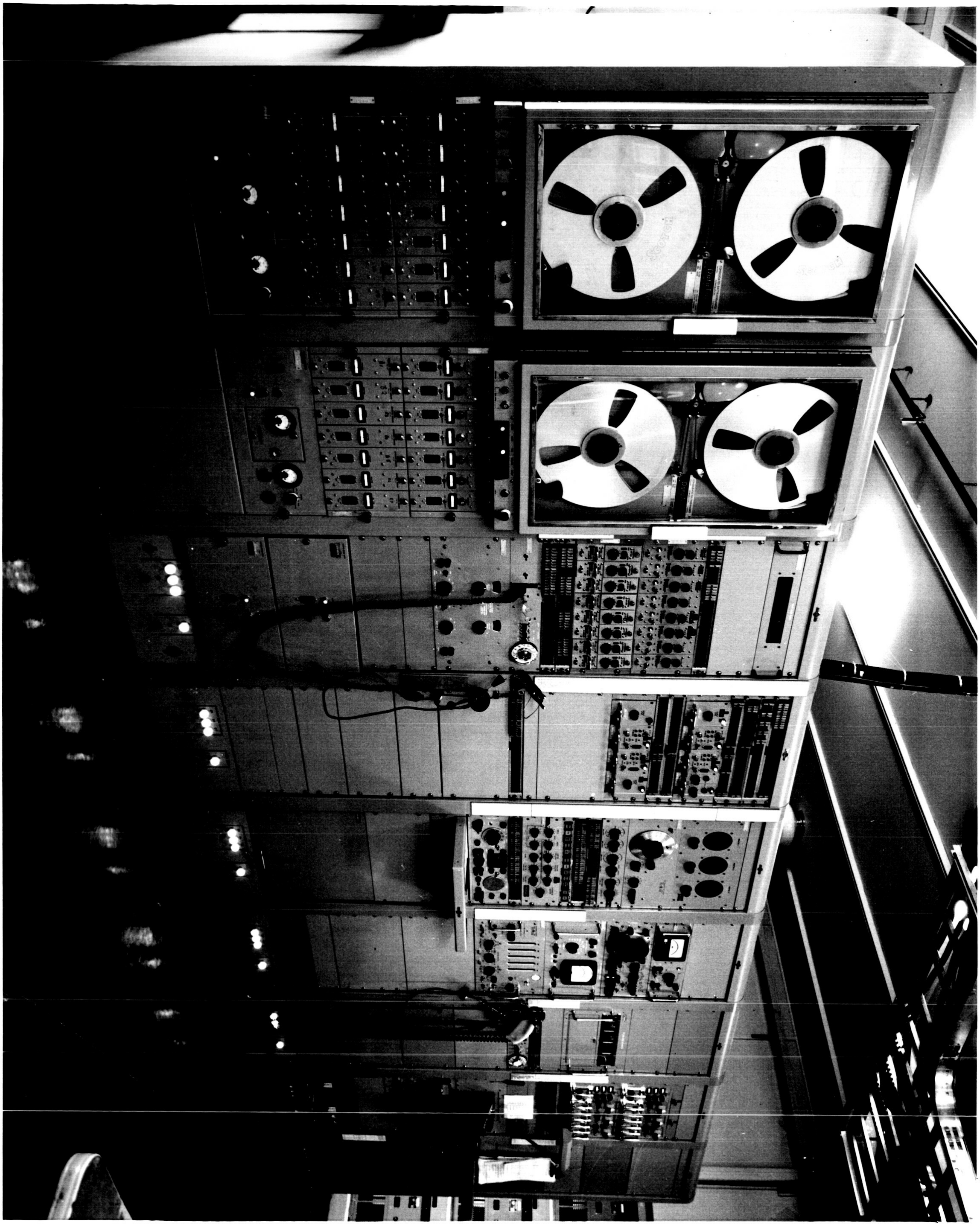
a. CONTROL BLDG
b. STATION PERSONNEL HOUSING
c. GUARD HOUSE
d. MESS AND RECREATION BLDG
e. HYDRO–MECHANICAL BLDG
f. DORMITORY
g. TO TRANSPORT AND GENERATOR BLDG

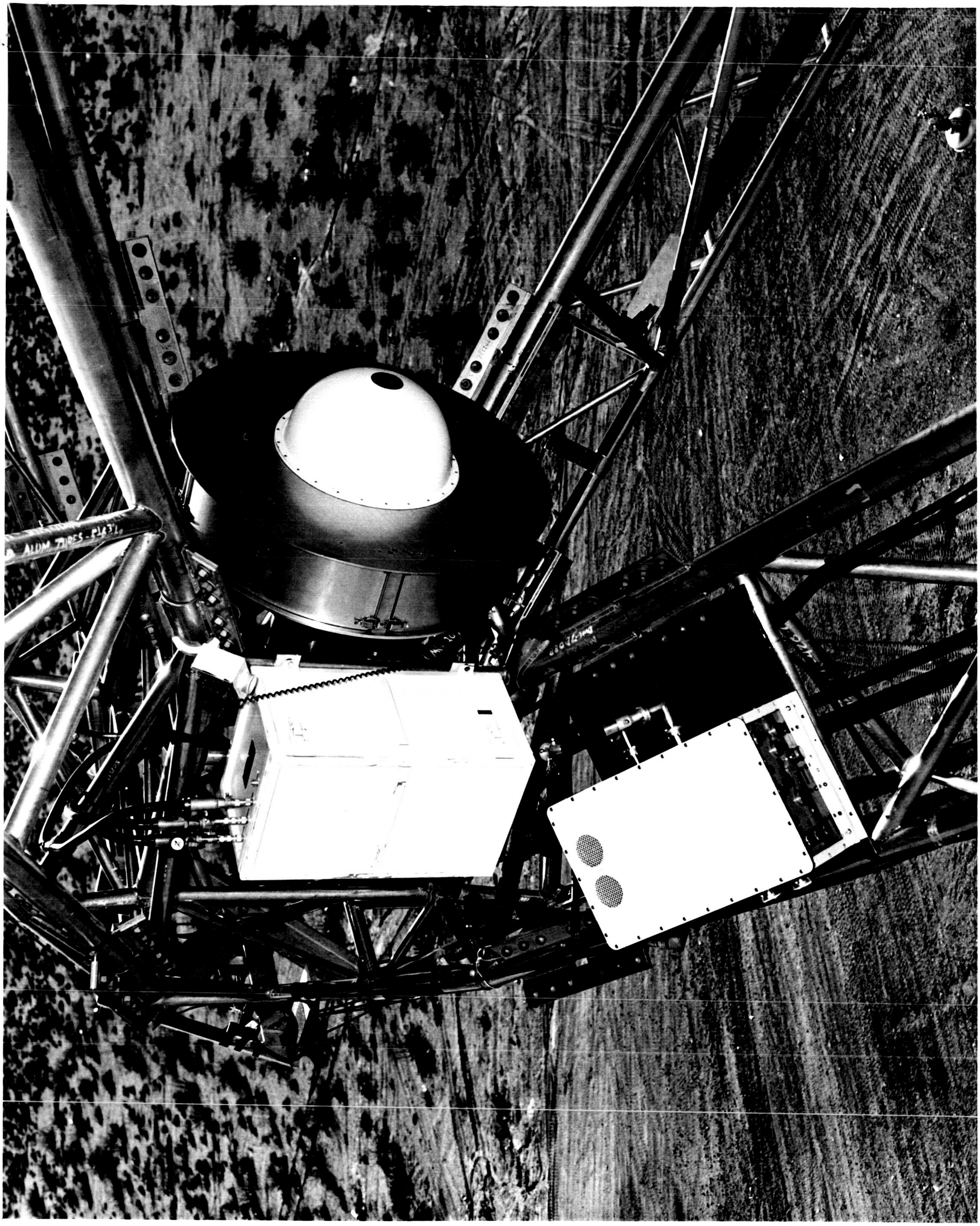


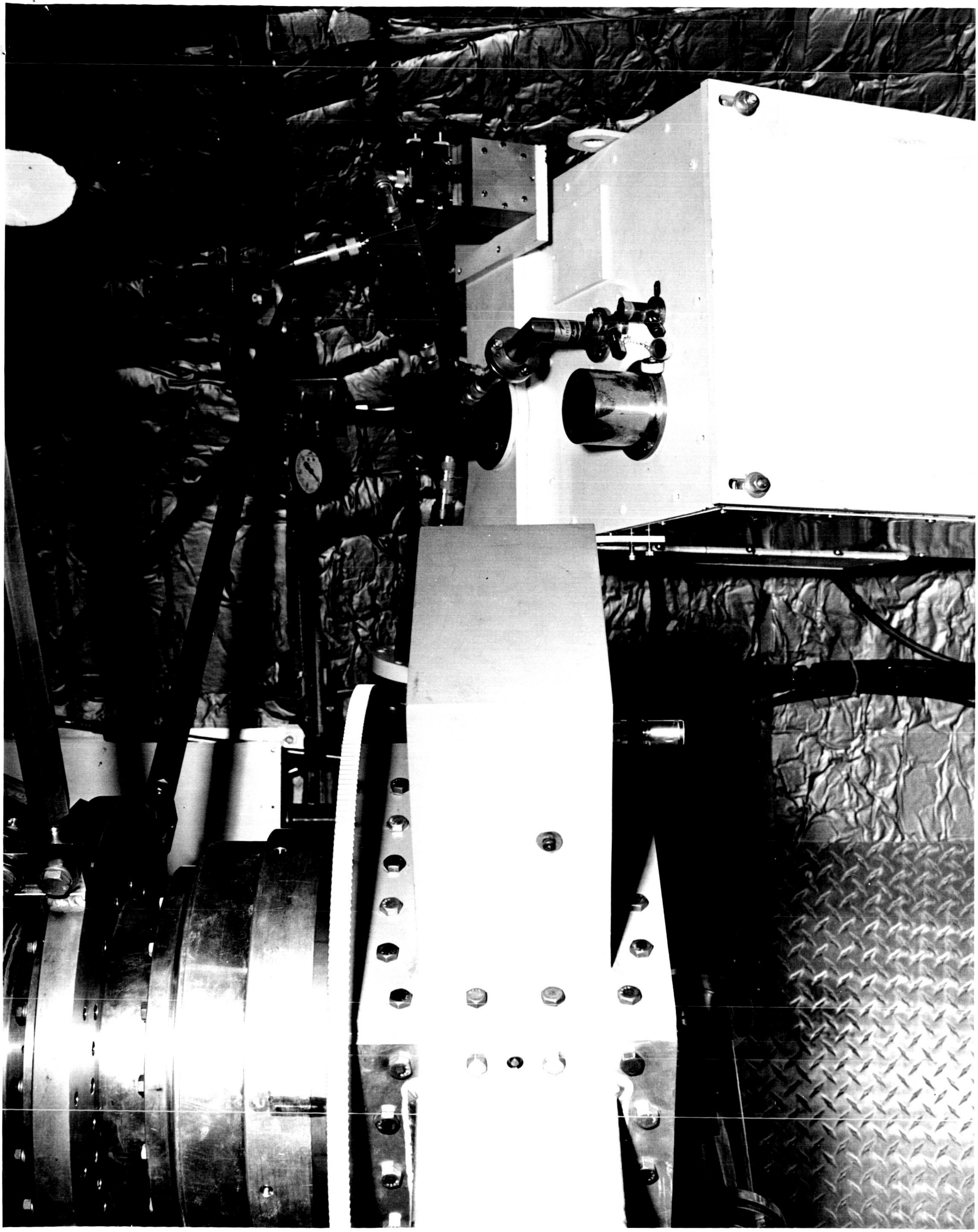
a. GUARD HOUSE
b. DORMITORY
c. WATER STORAGE TANK
d. SYSTEM ENGINEERING, ADMINISTRATION AND CAFETERIA BLDG
e. TRANSPORTATION BLDG
f. GENERATOR BLDG
g. CONTROL BLDG
h. STORAGE BLDG AND FUTURE MACHINE SHOP
i. HYDRO-MECHANICAL BLDG
j. COMMUNICATIONS AND OPERATIONS BLDG

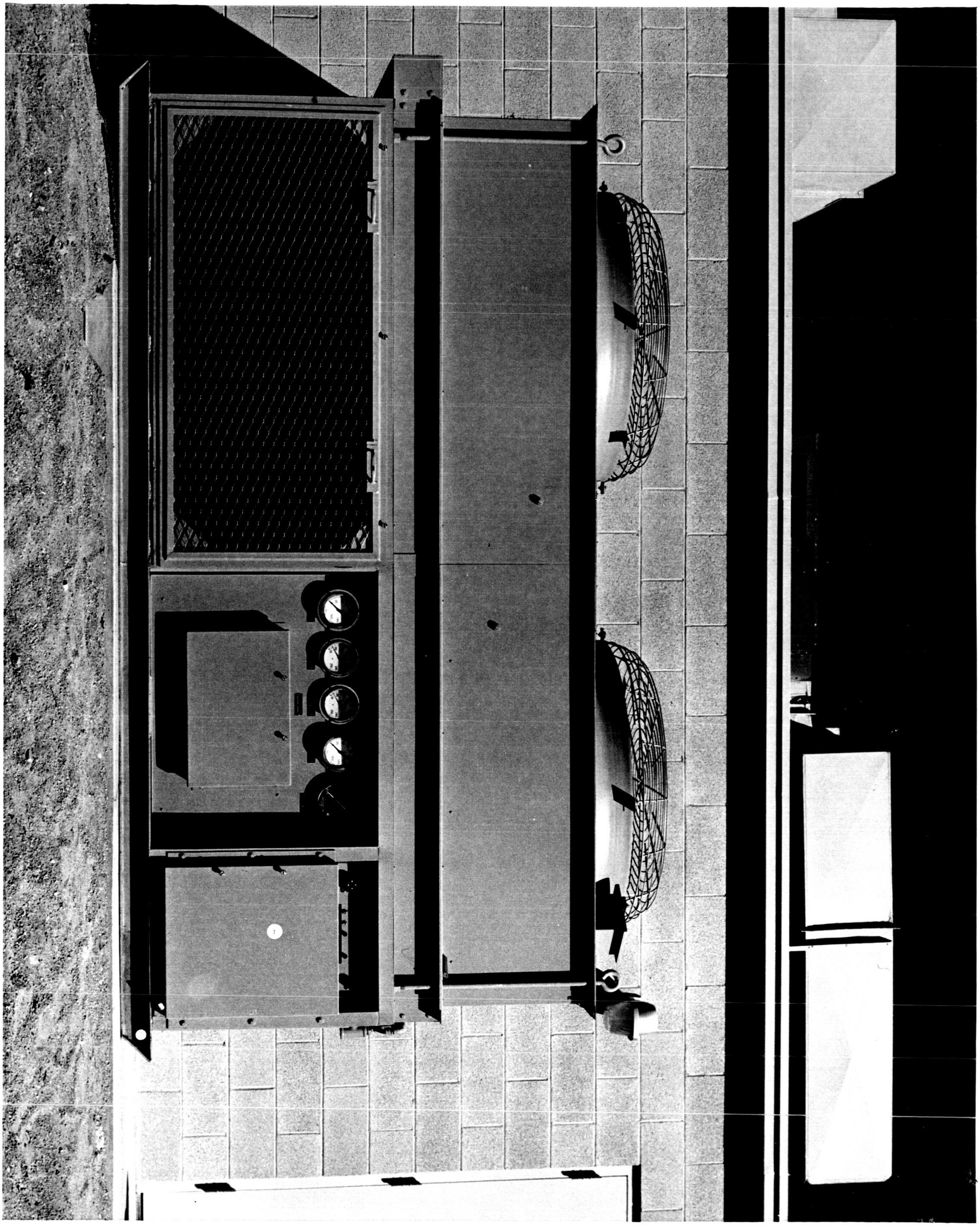

GROUND COMMAND SUBSYSTEM
SYSTEM AUXILIARY PANEL
ERROR TEST CONDITION
SYSTEM OUTPUT LEVEL
BASS BOOST
COUNTER
SCOPE CHANNEL 1
SCOPE CHANNEL 2
SCOPE SYNC
TIMED START
POWER SUPPLY
CMC

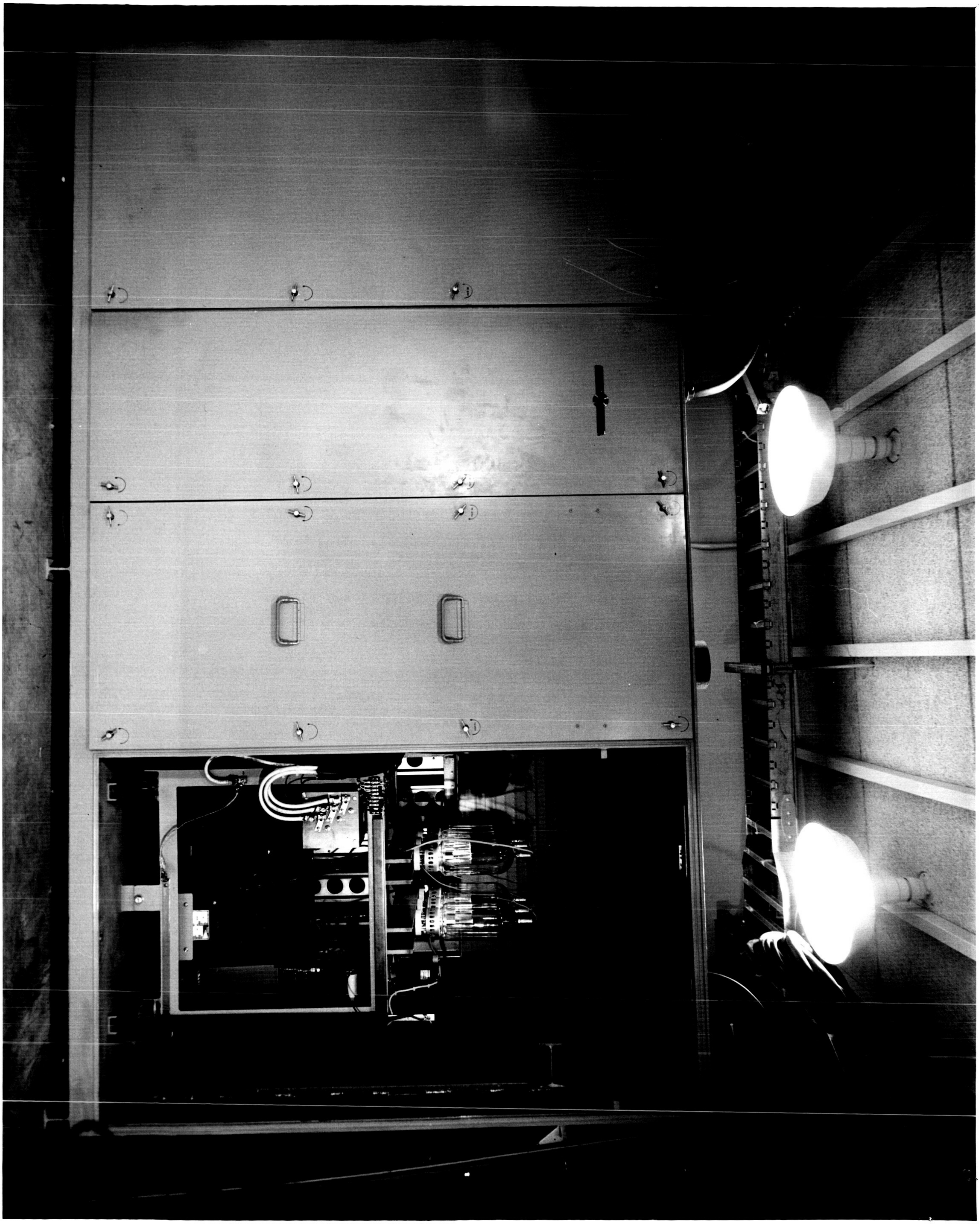


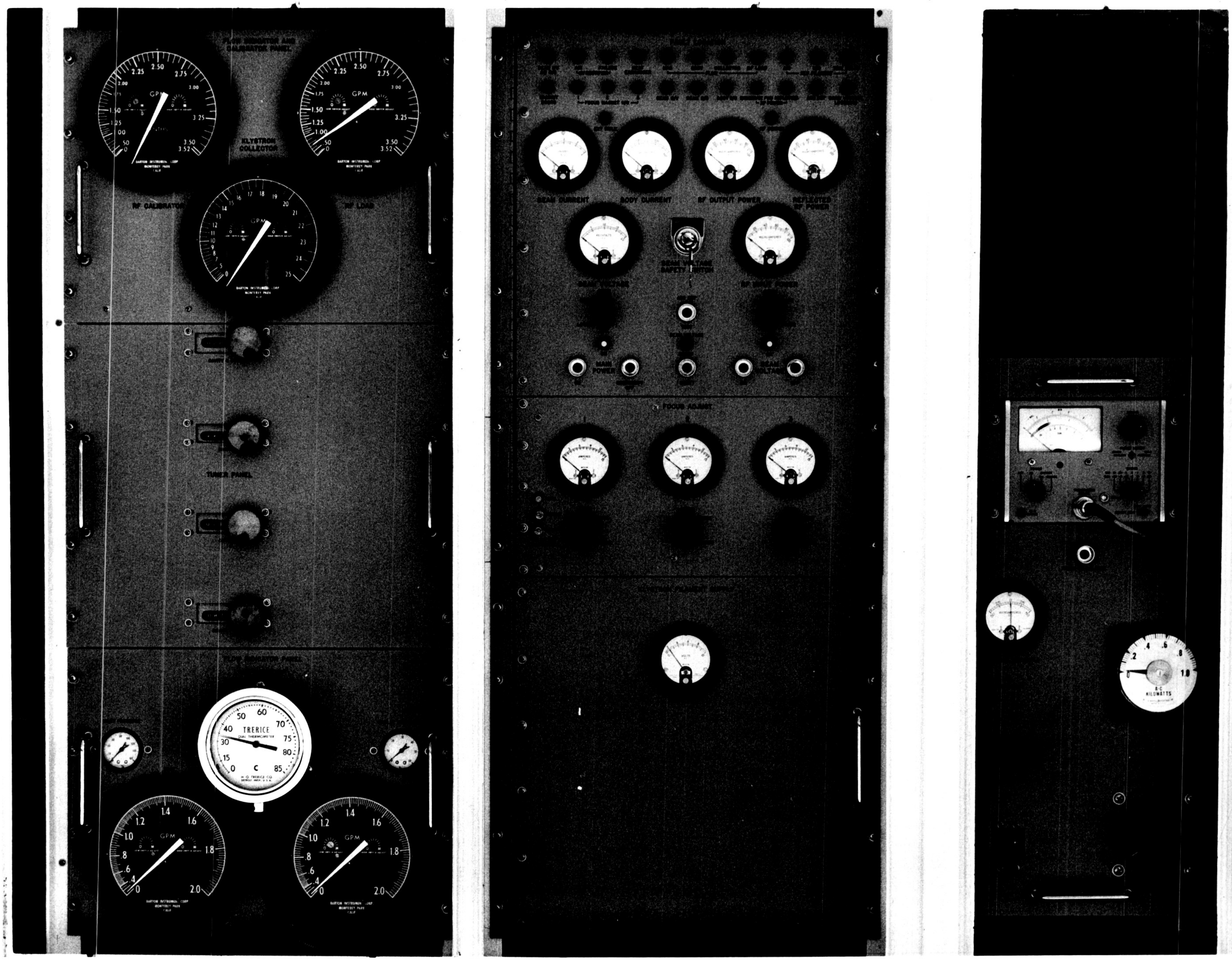




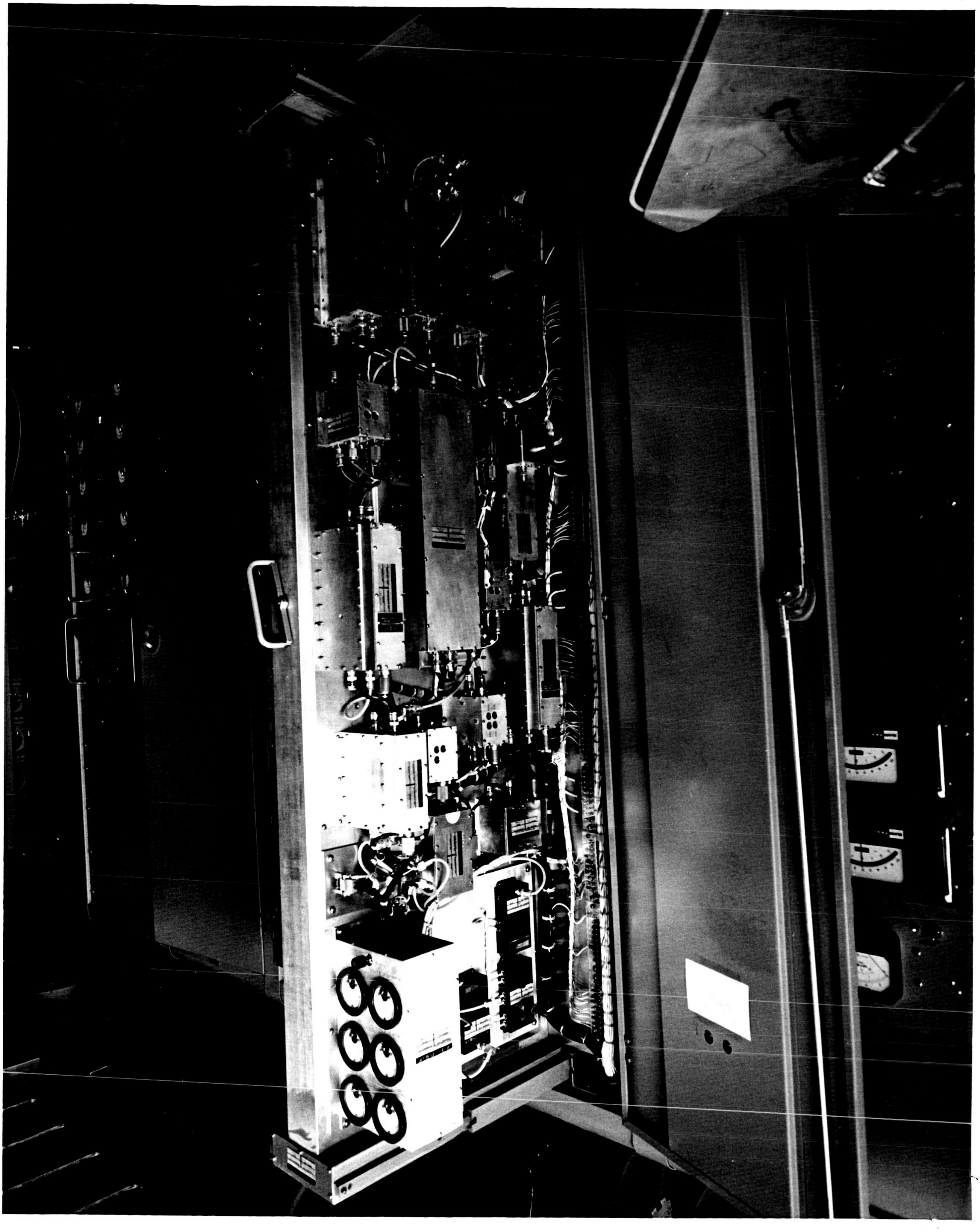


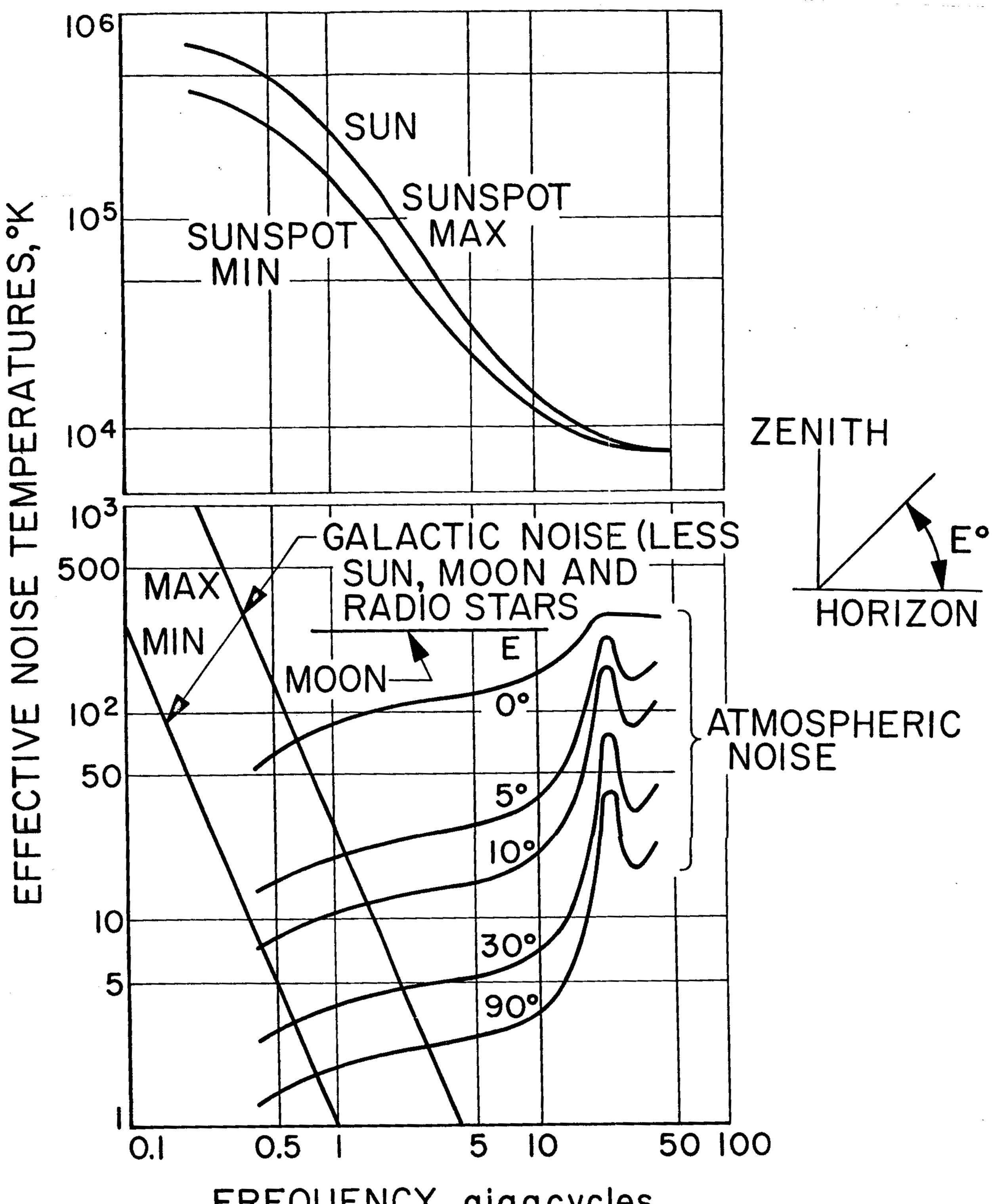






KLYSTRON COLLECTOR
RF CALIBRATOR
RF LOAD
TUNER PANEL
BEAM CURRENT
BODY CURRENT
RF OUTPUT POWER
REFLECTED RF POWER
BEAM VOLTAGE SAFETY SWITCH
FOCUS ADJUST
TRERICE
A-C KILOWATTS





GALACTIC AND ATMOSPHERIC NOISE TEMPERATUR
(APPARENT SURFACE BRIGHTNESS FOR THE MOON AND THE S
(REF 7 AND 8)